Summary of 2004 Workshop
Making Science Work for Suisun Marsh

By

Randall L. Brown

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The Bay-Delta Science Consortium

The San Francisco Bay-Delta Science Consortium (the Consortium) is a relatively new organization with the mission "to foster collaboration and the practice of interdisciplinary science in the San Francisco Estuary." In pursuit of this vision, the Consortium unites fifteen universities, private organizations, and Federal and State agencies involved with research, monitoring, and education in the estuarine system. Leaders from the member institutions regularly meet to communicate their needs and interests, brainstorm ideas, and provide guidance for Consortium-sponsored collaborative projects such as the Suisun Marsh workshop. For more information on the Consortium, please visit http://www.baydeltaconsortium.org.

Acknowledgements

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Executive Summary

The Suisun Marsh and its Management

In March 2004 the Bay-Delta Science Consortium sponsored a workshop to bring together, for the first time, a broad group of scientists, managers and stakeholders to engage in a scientific discussion of the marsh. Until then most comprehensive discussions of Suisun Marsh and its management occurred in testimony and cross examination before a regulatory agency such as the State Water Resources Control Board (SWRCB). The workshop purpose was to present and share data, information, and ideas to help ensure that the best available science will drive restoration and management decisions in the marsh. The workshop consisted of 31 presentations on various aspects of the marsh's physical and biological systems, its management infrastructure, and thoughts on restoring (re-creating) an additional 5,000 to 7,000 acres of tidal marsh. A significant portion of the workshop was allocated to discussion among the speakers and other attendees.

The 115,000 acre Suisun Marsh is an important ecological feature of the San Francisco Estuary, containing a large percent of the wetlands remaining in and around the estuary. The Marsh is home to an impressive fauna - 221 bird species, 45 mammal species, 16 species of reptiles and amphibians, and more than 50 species of fish. Twelve of these animals are listed as threatened or endangered pursuant to either the state or federal endangered species acts - 1 mammal, 6 birds, 4 fish, and 1 amphibian. During the fall and winter, the marsh provides a temporary home for a significant portion of the migratory waterfowl wintering in California. In turn, more than one-half of the waterfowl using the Pacific Flyway may winter in California. As shown by the number of birds using the marsh, it also provides important habitat for many non-game species.

Suisun Marsh terrestrial and avian communities are supported by a complex plant assemblage ranging from salt tolerant pickleweed to more brackish water plants such as alkali bulrush and brass buttons. Two plants in the marsh, Suisun thistle and soft bird's beak, are listed as endangered. Microscopic and barely macroscopic plants and animals in the marsh channels (the plankton) support the ever evolving fish population. All Marsh biotic communities have been impacted by numerous species of plants and animals that have been introduced from outside California (alien species) - either accidentally or on purpose. Overall the total numbers of fish captured in Marsh channels has decreased during the 1979-2003 period of record, perhaps mainly in response to the 1987-1992 drought. Fish numbers did not return to pre-drought levels in the post-drought period.

Suisun Marsh is located just seaward of the confluence of the Sacramento and San Joaquin rivers, and the salinity of water entering Marsh channels is a function of tidal forces, the physical configuration of the marsh and surrounding channels and the amount of freshwater flow. The amount of freshwater flow is in turn affected by annual and seasonal variations in precipitation (both snow and rain in the Sierra Nevada, the Cascade Mountains, and the coast range) and in the amount of water stored and diverted by an extensive Central Valley water management infrastructure. The State Water Project and the federal Central Valley Project divert large quantities of water from Sacramento-San Joaquin Delta, just upstream of the marsh, for customers in the Bay Area, the San Joaquin Valley and southern California. These diversions can affect the salinity of water reaching the northern estuary and the marsh and their biotic communities. In addition riparian and other diverters in the watershed lower the amount of water entering the Delta.

For the past 150 years, considerations for waterfowl production and hunting have provided much of the impetus for managing Suisun Marsh. Originally the hunters shot birds mostly to meet demand for waterfowl in San Francisco markets and restaurants. The hunters then began to acquire property in the marsh for recreational hunting - the birth of the duck clubs. For a relatively brief period farmers grew an wide array of crops in the marsh, but the salt content in marsh channel water, especially during drought years, caused agriculture not to be sustainable in the long term. The long-term salinity record for the marsh, as estimated from core samples, indicates that flows into the marsh have been quite variable, with extended drought periods.

The historic marsh consisted mostly of a series of ponds connected directly to the estuary - i.e., tidal marshes. Today's Suisun Marsh consists of 158 parcels of private land managed for waterfowl production, plus another 15,000 acres of public land that are managed for waterfowl and for protection of listed and sensitive plant and animal species. Most of the land managed for waterfowl production is now behind levees that limit tidal exchange between the land and the channels. Oxidation and other factors have lowered the land surface behind the levees (subsidence) and the relatively soft material underlying the earth levees makes levee maintenance difficult and expensive. As was dramatically shown in February 1998, a combination of high tides, winds and barometric pressure differentials can result in the levees being breached - at more than 60 locations in this instance.

It must be emphasized that, although at present Suisun Marsh is very different from the historic marsh, it continues to provide habitat for a wide variety of plants and animals. The Marsh still provides these ecological benefits because private duck club owners and members have worked, often for generations, to maintain the land's habitat values. Ducks are not the only animals that take advantage of wetlands found on the duck clubs. Without the dedication of waterfowl managers and hunters, much of the land in the marsh might be covered by streets and lawns instead of an ecologically valuable brackish water community of plants and animals.

From the 1960s through the mid 1990s, Suisun Marsh management has been based on the following hypothesis (conceptual model) postulated by California Department of Fish and Game wildlife biologists:

- Waterfowl use in Suisun Marsh is greater than that in the Napa Marsh - thus waterfowl managers in the northern estuary should focus their efforts on Suisun Marsh
- Waterfowl food resources are greater in brackish marshes than in more saline marshes.
- Alkali bulrush is the most important waterfowl food in brackish marshes.
- Alkali bulrush seed production is dependent on the proper combination of soil salinity and flooding cycle.

This generalized conceptual model was one of the products of a Department of Water Resource (DWR) and DFG fish and wildlife study initiated in the early 1960s to assess the potential effects of the State Water Project (SWP) that would begin diverting water from the Delta later in that decade. With respect to the effects of the SWP and the CVP which had been diverting water from the Delta since the 1950s, the hypothesis was that the primary wildlife need related to the SWP (and CVP) was maintenance of water salinities needed to grow alkali bulrush and other associated brackish marsh plants in Suisun Marsh. A corollary hypothesis was that SWP and CVP operations would adversely impact the quality (salt content) of the water available to the marsh, and that the projects would have to take measures to mitigate for the anticipated adverse impacts.

Some main points from the conceptual model and hypotheses are:

- The focus was on waterfowl.

- With the marsh configuration existing in the 1960s, the focus was on managed wetlands.
- The focus was on providing water of suitable quality to the managed wetlands to grow target wetland species such as alkali bulrush.
- Although not stated explicitly, the focus was on the marsh itself, not the marsh as an integral component of the San Francisco Estuary ecosystem.

Over the past three decades, the original conceptual model, as adopted in regulatory hearings by the SWRCB, has driven environmental protection efforts in the marsh. DWR and the USBR have spent over $100 million to develop plans of protection, provide and maintain physical facilities (for example, diversion structures, the Suisun Marsh Salinity Control Gates), monitor salinity, fishes and other system components, and purchase and/or maintain land to mitigate for direct impacts of project operation and facilities on listed and sensitive species. Suisun Marsh landowners have also expended considerable sums to achieve the protection goals.

Since the mid 1990s there has been movement towards a revised conceptual model of Suisun Marsh and how it interacts with the estuary. The 1995 Delta "Accord" and creation of the CALFED Bay-Delta Program provided part of the impetus to move from single species to ecosystem management, Some attributes of this yet to be completed model include the following:

- The marsh is an integral part of the estuary and what happens in the marsh affects the rest of the estuary.
- Ecological goals have been expanded from simply producing waterfowl to protecting the ecosystem and the many listed and sensitive species that are part of that system.
- Because of a combination of rising sea level, changes in precipitation patterns (and flows), and subsidence of land behind the levees, increased consideration is being given to levee stability and chances of flooding.
- The is increasing interest in recreating more tidal marshes in the San Francisco Estuary and in Suisun Marsh.

To further develop the ecosystem goals implicit in the revised conceptual model, The California Bay-Delta Authority has established a multi-agency Charter Group to help agencies, landowners and stakeholders prepare a new Suisun Marsh management plan and science agenda. This plan is intended to allow managers to meet DWR and USBR mitigation requirements, provide for waterfowl protection and hunting on private and public lands, and; provide broader ecological benefits in the marsh. This workshop is part of the process that can lead to a science based management plan for the Suisun Marsh. An explicit assumption in this process is that private managed wetlands will continue to be an integral and important component of Suisun Marsh management.

Conceptual Models

To help expand our understanding of Suisun Marsh biological, physical and chemical processes, the workshop stressed the development and use of conceptual models. Conceptual models are explicit statements of the way the modeler thinks the way the system, or an individual component within the system works. Conceptual models help identify gaps in knowledge and are integral components of adaptive management. The speakers at this workshop presented several conceptual models for consideration and the Charter Group is developing additional conceptual models as part of its management plan. Several conceptual models are included in this report and should be used when identifying gaps in our knowledge of how the marsh works. The models can also be a major asset in developing a Suisun Marsh science agenda.

Climate Change

The presentation on potential climate change and its effects on hydrology and salinity brought an message home to estuarine and wetlands managers. Global climate models indicate that over the next century we can expect air temperatures to rise 2-6 degrees C. This temperature increase will cause sea level to rise and will affect the climate and hydrology of northern California in unknown ways. Under one likely scenario, the annual amount of precipitation in the Central Valley watershed will remain relatively unchanged but the seasonal distribution will change, with more early winter rains at higher elevations in the Sierra Nevada. This change in precipitation pattern could result in more flooding during the winter months and decreased flows from snow melt during the spring and early summer months. In the past 10-20 years we have already seen the elevation of snow pack in the Sierra rising. Marsh planning should consider the effects of climate change on water supplies and estuarine salinity, as well as the effects of increased flooding and chances of more levee failures. Forecast sea level rises will exacerbate the levee maintenance problems.

Restoration

In the marsh and the rest of the estuary we are “re-creating” tidal marsh under modern conditions and constraints on lands where it once existed; we are not “restoring” the marshes of 1850 and before. When thinking about tidal marsh restoration one must consider that restoration changes marsh “geometry,” affects tidal propagation over a wide area, produces and consumes good stuff and bad stuff, and that process understanding is the key to restoration success. For example, the Suisun Marsh could be a net producer of organic carbon - which is good for the food web but may be bad for drinking water supplies. We do not have much tidal marsh remaining in the estuary thus it is difficult to predict ecosystem effects of tidal wetlands restoration. Many of the attendees recommended starting with relatively small projects couched in an adaptive management framework.

The salt ponds in South San Francisco Bay and in the Napa Marsh do provide useful information about restoring a highly modified system. These studies have indicated that:

- Managed ponds and salt ponds are valuable wetlands that provide habitats supporting high densities of some species.
- Conversion of existing wetlands may result in increases in some populations (landbirds, rails), but decreases in other populations (shorebirds, waterfowl).
- To optimize resource values, a balance of habitats must be maintained at the regional landscape scale.
- Population viability analyses may be valuable tools to evaluate when it is most beneficial to restore tidal marshes for target species.

Suisun Marsh Science Agenda

The workshop presentations clearly demonstrated that the science base in Suisun Marsh is relatively weak. The conceptual models provide ideas as to where the significant data gaps lie and some these data gaps and information needs are identified in the report. The report contains a recommendation that the Charter Group or other entity take the lead in developing a science agenda for the marsh. Such an agenda will take time and cooperation of all parties, including landowners.

Shortly after the March 2004 workshop an ad hoc interdisciplinary group of university and agency scientists developed and implemented a pilot monitoring program for a limited portion of the marsh. The pilot program staff used borrowed equipment, agency staff and a limited amount of seed funding. This pilot program is an example of what can be done with limited resources when there is a need for information. Its collaborative nature should be a model for other programs in the marsh and the estuary as a whole.

Overall Conclusion

The Suisun Marsh workshop was a success in that it brought together a large and diverse group of scientists, managers and stakeholders. The workshop was also successful in that the presentations and discussion clearly showed that many of the decisions about Suisun Marsh were based on conceptual models and scientific data that should be updated. A particularly encouraging development after the workshop was the initiation of a pilot study of some important aspects of the marsh system. Although this pilot study was probably not a direct result of the workshop, the fact that it came into being in such a short time, and with such a limited amount of new funds, demonstrates the potential for strong, process based science in the marsh.

Introduction

This paper is a product of a March 2004 workshop convened by the Bay-Delta Science Consortium (BDSC) to describe several aspects of California’s Suisun Marsh and to explore ways in which science can be used by scientists and managers to evaluate alternative management scenarios. (See Appendices A and B for the workshop agenda and attendees respectively.) The workshop and this paper emphasize the use of conceptual models as important tools for incorporating scientific understanding in marsh planning.

The workshop was convened with the purpose of helping ensure that the best available science is driving restoration and management decisions in the Suisun Marsh. Specific goals were to:

- Provide a forum to discuss pressing issues related to science, restoration, and management in the marsh.
- Present and discuss the general state of knowledge in the marsh
- Present and discuss resource management needs and constraints in Suisun Marsh.
- Synthesize science and resource management in the marsh by listing data gaps in scientific knowledge and prioritizing them based on resource management needs.
- Identify data gaps that have a high potential for inter-disciplinary science that will promote institutional collaboration in the marsh.

- Assist the Suisun Marsh Charter Group with its efforts to integrate science with the Suisun Marsh Plan of Implementation.

The goal in writing this summary is to convey a general understanding of how the marsh works, how it has been managed, and its relation to the larger San Francisco Estuary system. In keeping with the workshop goals, I also highlight some of the major scientific uncertainties and suggest the types of studies that may help reduce these uncertainties. It must be emphasized that this is only a partial look at a very complex system - complex both from ecological and management perspectives.

Much of the material in this paper is based on information presented and discussed at the workshop. To meet the charge of the workshop planning committee to develop more of a synthesis report, I also supplemented information from the presentations by the open literature and numerous agency reports. The workshop speakers and members of the workshop organizing committee have reviewed drafts of this paper and it has been modified it in response to their comments and suggestions. I assume responsibility for the report's final contents.

California's Suisun Marsh (Figure 1) is the largest contiguous estuarine marsh remaining in the continental United States and, with a total of about 116,000 acres, contains more than ten percent of California's remaining wetlands (DWR 1999). The marsh itself consists of 52,000 acres of managed wetlands, 27,700 acres of upland grasses, 6,900 acres of tidal wetlands, and 30,000 acres of bays and sloughs. The managed wetlands are divided into 158 private parcels (mostly duck clubs) and more than 15,000 acres of public lands managed by the California Department of Fish and Game (DFG).

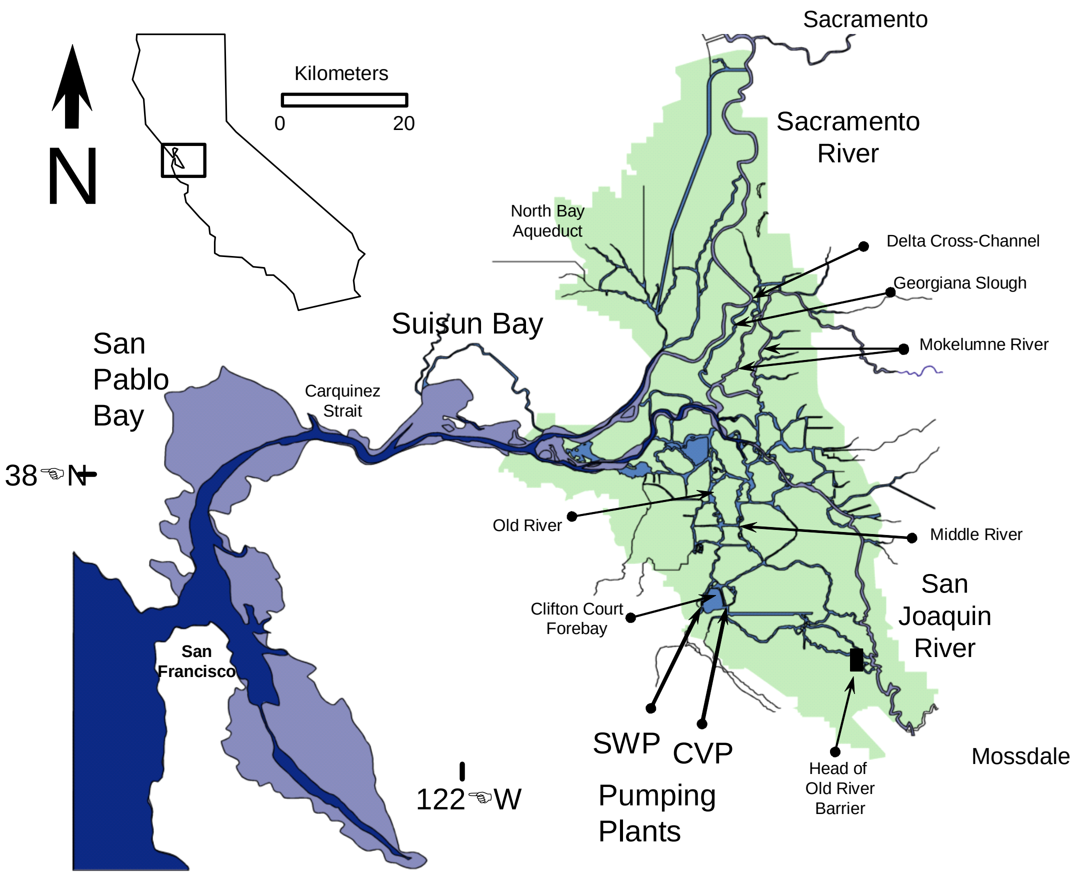


Figure 1. Map of San Francisco Bay-Delta Estuary and Suisun Marsh

The Suisun Marsh is important to California and the nation for a variety of reasons. During the fall and winter, the marsh provides a temporary home for a significant portion of the migratory waterfowl wintering in California (Burns et al. 2003). In turn, more than one-half of the waterfowl using the Pacific Flyway may winter in California (Burns et al. 2003). The marsh provides essential habitat for 221 bird species, 45 mammal species, 16 species of reptiles and amphibians, and more than 40 species of fish. The marsh's complex biotic community includes such charismatic macro-fauna as Chinook salmon, river otters and Tule elk. The marsh is also home to numerous species of plants and animals that receive protection pursuant to the federal Endangered Species Act (ESA) or the California Endangered Species Act (CESA). A 1999 biological assessment of a major program in the marsh considered the impact of the action on 43 special status plant and animal species as denoted by the US Fish and Wildlife Service (USFWS) (DWR and USBR 1999).

In addition to the ecological, waterfowl hunting, and other values of the marsh itself, Suisun Marsh is an integral component of the San Francisco Estuary system, including the Sacramento-San Joaquin Delta (Figure 1) - one of the most developed estuarine systems in the world (Nichols et al. 1986). The Sacramento-San Joaquin Delta (the Delta) is a key element of California's water supply structure. In an average year, federal and state water project pumps in the southern Delta divert more than five million acre-feet (maf) of water from the Delta for use on farms in the San Joaquin Valley and by urban and industrial users in the San Francisco Bay area, the Central Coast, and southern California. (In general terms two out three Californians receive part of their water supply from the Delta.)

Water project diversions in the Delta and diversions and storage upstream reduce the amount of water leaving the Delta and can influence the salinity (salt content) of water in the lower estuary, including Suisun Marsh. The salinity of water entering the marsh can affect the abundance and distribution of plants and animals in the marsh. Conversely, marsh activities (including construction and maintenance of levees surrounding managed wetlands) can affect water and salt movement in the estuary and the salt content of water in the Delta. Salt content is in an important consideration for urban and agricultural uses within the Delta and in downstream water service areas.

The Suisun Marsh has been actively managed to some degree for the past 100 + years, with the recent focus on managing the marsh for waterfowl production and hunting. Since the 1970s much of the emphasis has been on ensuring that the marsh receives water of adequate quality to produce the plant communities thought necessary to support waterfowl production. As will be shown in this report, marsh management is a complex function of water levels and water quality and movement of water off and on duck clubs and public managed wetlands, tempered by regulatory constraints that affect the ability of managers of clubs and public lands to fill and drain their diked wetlands.

The marsh is managed in the context of an extensive institutional structure and its management can not be fully appreciated without a thorough understanding of who the players are and how they interact. It is beyond the scope of this report to provide a detailed account of this structure but Table 1 summarizes some of the key players and their responsibilities. It must be kept in mind that the list is not inclusive and only hints at the way the interaction of the agencies in marsh management.

Table 1. Key agencies and groups having major responsibilities in managing Suisun Marsh.

Agency Name	*Description of Responsibilities in Managing Suisun Marsh*
Suisun Resource Conservation District (SRCD)	The SRCD has the primary local responsibility for regulating and improving water management practices on privately owned lands within the primary management area of the Suisun Marsh.
California Department of Water Resources (DWR)	Although DWR has several functions relating to Suisun Marsh Management, its involvement in the marsh is mainly associated with operation of the State Water Project (SWP) and mitigation of any adverse effects.
California Department of Fish and Game (DFG)	DFG manages 12,000 acres of managed wetlands in the marsh for hunting, fishing and other recreational uses, administers CESA activities to protect special status species, and manages habitat intended to mitigate for SWP and other impacts.
US Bureau of Reclamation (USBR)	The USBR operates the Central Valley Project (CVP) which diverts water from the southern Delta through the Tracy Pumping Plant and works with DWR, DFG and SRCD to avoid, minimize or mitigate for its impacts in the marsh.
Bay Conservation and Development Commission (BCDC)	The BCDC is specifically charged with protecting the Suisun Marsh, the largest remaining wetland in California, by administering the Suisun Marsh Preservation Act in cooperation with local governments.
California State Water Resources Control Board (SWRCB)	Through its water quality and water rights authorities the SWRCB promulgates water quality standards for the Suisun Marsh and conditions DWR and USBR water rights permits to meet those standards.
US Fish and Wildlife Service (USFWS)	As part of its ESA authority, the USFWS issues biological opinions on operation of the State and federal water projects, including those facilities in the marsh (e.g. the MSSCG) and may require other federal permits be conditioned to protect listed species.
NOAA Fisheries	NOAA Fisheries has federal ESA responsibility for anadromous fish including winter and spring Chinook salmon and steelhead and has conditioned operation of the MSSCG and water diversions in the marsh to protect these species.
CALFED Bay-Delta Authority (CALFED)	The 2000 CALFED Record of Decision (ROD) calls for creation of an additional 5,000 to 7,000 acres of tidal wetlands in Suisun Marsh. Through its Ecosystem Restoration Program, CALFED funds marsh restoration projects.
Charter Group	The Suisun Marsh Charter, and its multi-agency member group was established in 2000 to develop a regional plan that balances implementation of the CALFED program with other preservation, management, and restoration programs in the marsh.
Solano Mosquito Abatement District	To limit mosquito production in wetlands the Solano Mosquito Abatement District may restrict the time when ponds can be flooded up in the fall.
The US Army Corps of Engineers (USACE)	The USACE issues permits to DWR, DFG and SRCD for work in the marsh, including facilities (404 permits) and maintenance (Regional General Permits). These permits contain conditions designed to protect water quality and sensitive species.

The information in Table 1 focuses on marsh management. Many of the same agencies are involved in the scientific aspects of managing the marsh, including monitoring conditions, habitat and species in the marsh. Of particular importance in this area are:

- The Interagency Ecological Program (IEP) includes most of the State and federal agencies shown in Table 1. The IEP collects monitoring data in the marsh and other parts of the estuary. The IEP also conducts special studies such as passage of adult Chinook salmon at the Suisun Marsh Salinity Control Gates.
- DWR and DFG have specific monitoring requirements for water quality conditions, status of listed species and their habitat.
- The US Geological Survey is a member of the IEP and has a separate program, the Place Based Program, that recently moved into the marsh to look at contaminants as well as water and sediment movement. Another element of the USGS, the Biological Resources Division, has been studying waterfowl in the marsh and other parts of the estuary for many years.
- University of California, Davis researchers have been active in the marsh for the past 25 years with much of their work focusing on fish communities. Recently they have been looking at mercury in the marsh.

Using Conceptual Models in Suisun Marsh Restoration Planning

This brief discussion of conceptual models is based on the presentation by Zach Hymanson of CALFED. In the scientific context, a conceptual model is a formalized way of describing how we believe things work. Typically a conceptual model evolves from a collection of thoughts to a written narrative with supporting diagrams. Conceptual models are generally qualitative (descriptive), and may be considered a formalized way of organizing our thoughts. Among the benefits of written conceptual models are:

1. The models are explicit and thus can be reviewed by others. This review can result in revised, and more useful, models.
2. The models can be used to assess the strength of the information in each of the model links, as well as the relative importance of the links themselves. Using this knowledge scientists and planners can determine the relative importance of acquiring new information (research) or the likelihood that certain actions will result in a desired outcome (restoration planning).
3. The models are part of a formalized planning process called adaptive management (Figure 2). Although the diagram looks somewhat complicated, in essence the iterative process involves:
   a. Defining a problem.
   b. Setting goals and objectives
   c. Describing how the system works - i.e. the conceptual model
   d. Taking actions to solve the problem and to achieve the desired goals and objectives.
   e. Acquiring information to determine how well the actions are working
   f. Feeding the new information back into the adaptive management process

g. If necessary, based on the new information, redefining the problem, the goals and objectives, the conceptual model, and the actions.

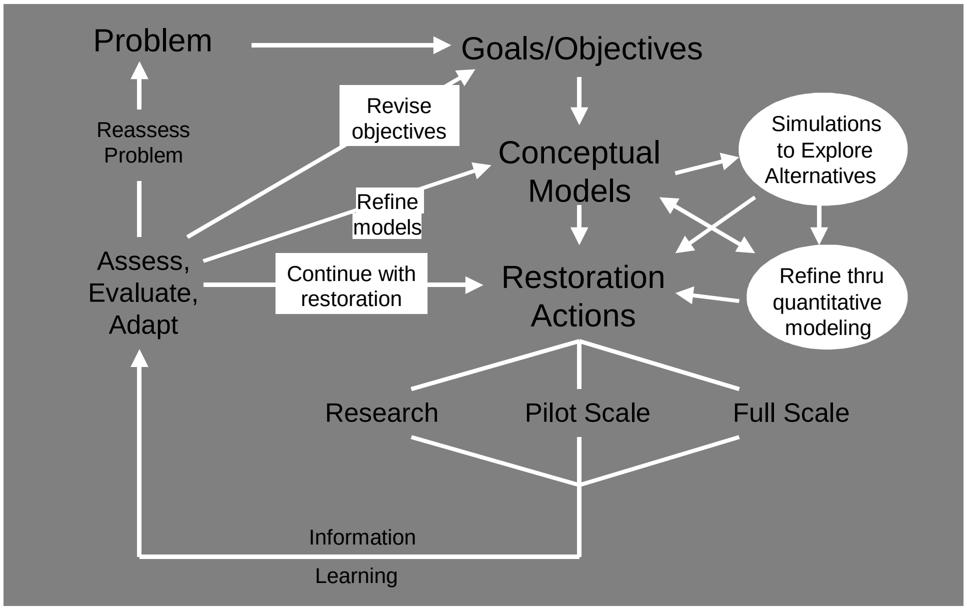


Figure 2. Conceptual models as part of adaptive management. (Source: Z. Hymanson.)

In restoration planning conceptual models are used to describe important habitat processes and functions, forecast effects of potential actions, identify areas of uncertainty, and identify factors affecting a desired outcome. The models may also provide an idea of what system measurements provide the most useful performance indicators - for example, the acreage of self-sustaining brackish tidal water marsh habitat created by a specific action.

In Suisun Marsh members of the Charter Group are working on models of tidal wetlands (USFWS lead), managed wetlands (DFG and SRCD lead), water quality (DWR lead) and species life cycle models (DFG lead). Some additional conceptual models were developed for this workshop and are discussed later in the report.

A few final points about ecologic conceptual models:

- They are almost always incorrect in that we don't fully understand what is going on.
- They will continue to improve as we learn more.
- They are essential to learning in that they make our understanding of what is gong on available for peer review and thus help us collectively identify and obtain the data necessary to refine the models.
- As our understanding increases we may be able to move from conceptual to predictive models - e.g. a computational model that allows us to evaluate the relative benefits of different actions. In reality, most ecologic predictive models are mathematical representations of our concept of how things work and may not represent the way they really work.

Conceptual models are often most useful when developed by an interdisciplinary group in that the models may involve chemical, physical and biological processes. In the marsh, and indeed the estuary and its watershed, conceptual models have been an under-utilized component of the scientific process.

The Evolving Suisun Marsh and Its Connection to the San Francisco Estuary

In this section I draw from the presentations and the literature to describe some of the physical and biological aspects of the marsh and its link to the estuary. The discussion is divided into two general time periods - the marsh before 1950 and the marsh since 1950. The division is arbitrary and is meant to capture the before and post water development era. As will become apparent, it was not always possible to maintain this separation in the text.

The Historic Marsh

Suisun Marsh has been an integral part of the estuary for several thousand years. According to Atwater (1979), about 8,000 to 10,000 ago, sharply rising sea levels dramatically changed the San Francisco Estuary shoreline and tidal marshes. By 6,000 years ago, sediment from local streams and the Sacramento and San Joaquin rivers had begun to maintain marshes and by 1850 these marshes covered about 500,000 acres. By the 1950s, filling or levee construction had decreased the marsh acreage around the estuary to approximately 50,000 acres of tidal marsh in the estuary - about one-fourth of the original (Van Royen and Siegel 1959).

The original Suisun Marsh contained a significant fraction of the more than 500,000 acres of marsh habitat found around the estuary before the Gold Rush. The Suisun Marsh of 1850 consisted of islands connected by a network of tidal sloughs. Much of marshland was flooded daily and seasonally by high tides and high stream flows during the late winter and spring. Salinity in the tidal sloughs varied seasonally due to the unconstrained affects of river flow - moderate to low salinity in the winter through early summer and high salinity for up to five months during the low flow season. The native vegetation before 1850 probably consisted of a mix of tules, cattails, rushes, saltgrass and pickleweed, with perhaps saltgrass being the dominant plant in most of the marsh.

To extend the marsh history even further into the past, at the workshop, Frances Malamud-Roam (UC Berkeley) described the use of stable carbon isotopes, pollen and diatom composition from a 3.5 meter core taken at the Rush Ranch located in Suisun Marsh to establish a paleosalinity record for the past approximately 3000 years. (Interested readers can find more information about site location, methods and results in Byrne et al. 1998.) The data (Figure 3) indicate that reduced freshwater flow (as estimated by the types of plants present in the core) entered the estuary 3000-2500 cal. yr. B.P., 1750-750 cal. yr. B.P., and around cal. yr. 1930 to present. The period 750 cal. yr. B.P. to 1930 was characterized by relatively high freshwater flows to the estuary. The decreased flows since 1930 were postulated to be due to a combination of droughts and upstream water development.

To rule out the possibility that tectonic activity may have strongly influenced the marsh record, Malamud-Roam presented core data from two nearby sites (Petaluma Marsh in San Pablo Bay and Browns Island east of Suisun Bay). All three marsh sites have similar chronologies, with no evidence of abrupt changes in sedimentation that would be expected if tectonic activity influenced the record at Rush Ranch.

The data demonstrate that freshwater flow to the estuary and it surrounding marshlands has been variable over the period of record. As will be seen later, global climate change has the potential to add another anthropogenic complexity to the amount of water entering the estuary from the Sierra Nevada and Cascade mountains.

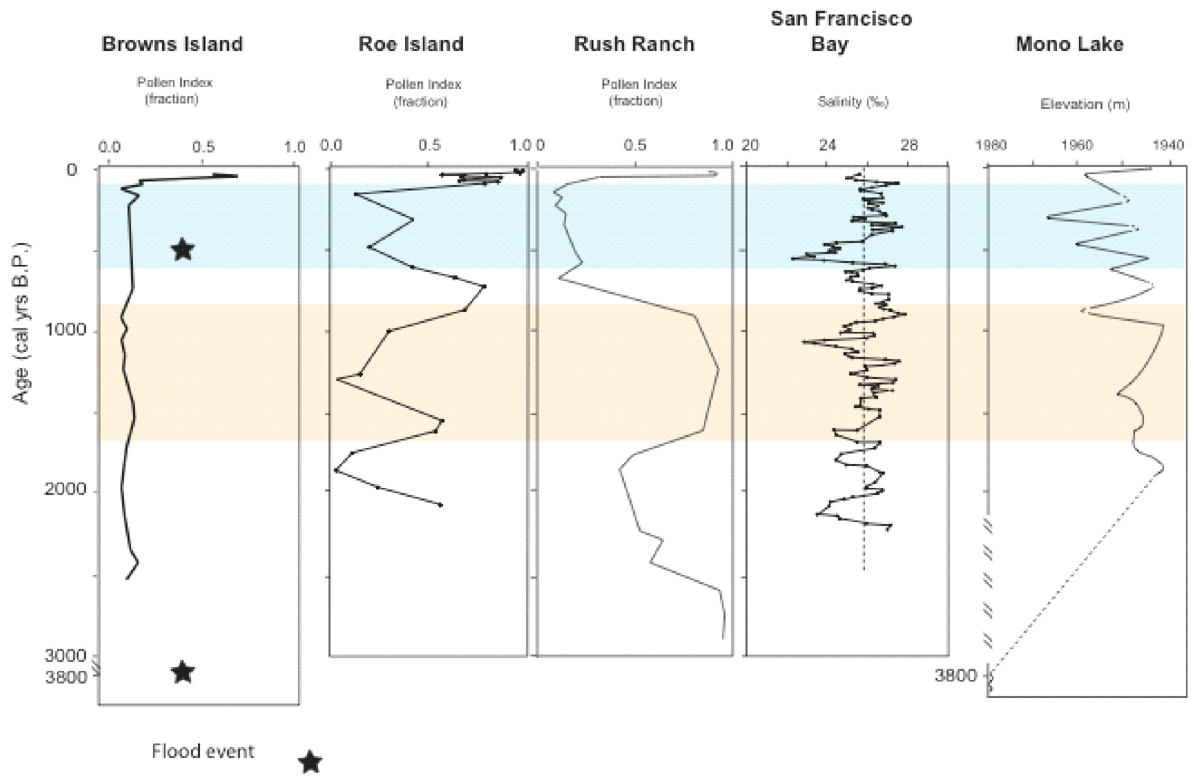


Figure 3. Reconstructed San Francisco Estuary record pollen core records from sites around the estuary. (Source: F. Malamud-Roam.)

Suisun Marsh began to change soon after the first wave of new immigrants came to California during the Gold Rush. The following is drawn from the presentation by Robin Grossinger (San Francisco Estuary Institute), Arnold (1996) and DWR (1999). Arnold (1996) in particular provides a fascinating account of the history of hunting and agriculture in the marsh. Material in Grossinger's presentation came from interviews with local residents and landowners about the marsh's rich history and he thanked them for their cooperation on the historical ecology project. He also noted that his work was a regional assessment and that there has not been a geographically specific assessment of Suisun Marsh. Historical maps of Suisun Marsh used in Grossinger's talk and others can be found at http://www.sfei.org/ecoatlas.

Suisun Marsh has a unique history in the San Francisco Estuary because of the persistence of waterfowl hunting - i.e. in the marsh waterfowl hunting and management became established in contrast to the rest of the estuary where waterfowl hunting declined. Also the marsh had a period of substantial agriculture use, whereas other nearby areas had less robust agricultural usage. At one time the marsh had a diverse range of crops, including hay, beans and asparagus, but agriculture use was short lived and geographically constrained compared with that of the Delta.

In the 1850s, the marsh was mostly tidal, with scattered ponds, few mud flats, presumably because the brackish water allowed plants to colonize lower in the tidal area. The area near Grizzly Island was all subtidal at that time.

An early source of information was the 1866 Coast Survey, which showed interesting features, e.g. ponds at the marsh's edge and a network of channels. An additional survey conducted in 1898 contained some additional information, including the railroad which first opened in 1878. The railroad is of particular importance to marsh management in that it brought waterfowl hunters into areas that had been previously accessed with difficulty. The early maps showed that tidal ponds were prominent landscape features that defined the marsh.

Much of the early activity happened on the marsh's west side. Events on the east side of the marsh were less documented - the first survey shows transitional pans associated with the upland edge. At the upland edge there were small creeks, like Green Valley Creek, with riparian corridors that flowed into the marsh. Other creeks were more spread out, and created extensive swampy areas and marsh edges.

From the 1850s through 1870s hunting started in marsh ponds with market hunting for San Francisco outlets dominating. The ponds were often named after people who hunted there. In the 1870s-80s sport clubs emerged and people began to own their ponds for personal use. Ponds were transformed into duck clubs thus the beginning of the duck club "industry." As described by Grossinger, in the 1890s there was a "Phantom Pond," which hunters spent many hours of trying to find. After locating it, they noted that they "commenced to hear a peculiar noise…[in their] excitement hurried along…disturbed a wildfowl sanctuary." This historical narrative showed how ponds in marsh were then "covered with wild fowl of every description," such as "Canada geese, white geese, swans, etc."

The original marsh ponds were converted from tidal to managed wetlands. Hydraulic mining debris of the 1860s filled in the subtidal area in Grizzly Island and the area became a mud flat. Subsequently this area, called the "King Tule," became marsh and was diked off. Close examination of maps and other data reveal the historical edge of marsh. Also traces of activities from the 19th Century can be found in today's landscape features.

Agriculture has made major contributions to the marsh's changing landscape. Although agriculture is no longer important in the marsh (a few hundred acres devoted to pasture and growing hay), agricultural land use had an earlier impact on marsh topography than waterfowl hunting. Agriculture took off before the duck clubs and in many parts of marsh, duck hunters retrofitted structures, berms, etc. left from agriculture practices. Agriculture in the marsh required a supporting infrastructure, including landings, levees to protect structures and crops, and the farmers often blocked off sloughs. Although extensive agriculture didn't persist in the marsh (mainly due to salinity problems, in particular high salinities associated with the prolonged drought of the 1930s), farmers blocked and redirected sloughs, and changed Suisun Marsh as much as duck hunters. With waterfowl management and development of duck clubs, more land was kept wet, perhaps with less subsidence. As waterfowl management increased, the land was altered to meet needs of hunters and duck club managers. Specifically, hunters needed access, parking lots, barns, lodges, landing, and clubs needed ponds for each complex.

South Francisco Bay provides a view of the evolution of marshes in another portion of the estuary. In 1857 there were natural ponds along the margins of South Bay, but by 1858, many of the ponds had been subdivided, into several compartments. These compartments allowed the harvest of salt in one area while keeping water in other parts. This salt harvest industry developed into bigger features, and finally conglomerated in to one large salt extraction operation. In contrast Suisun Marsh evolved as series of individual clubs with some managed public wetlands.

In Suisun Marsh there was a long period during which tidal habitat was converted to managed habitats. In early 20th-century maps one can see the outlines of original ponds and, structures, levees, ditches starting to connect ponds. Grossinger reflected that it would be interesting to find out how and why things were modified, manipulated, and adjusted for different purposes. Earlier managers may have knowledge about how the system worked and how it could be adjusted. This information could be useful for managing tidal and diked wetlands today. Part of the present habitat complexity in Suisun Marsh is due to historical land use and changes, like the extent and duration of agriculture, the crops grown (and their associated infrastructure) tide gates, levees, sloughs, and facilities that modified water (and particle) movement.

The major points to be gained from Grossinger's review of the historical ecology of Suisun Marsh are:

- There are similarities and differences between the marsh and the rest of the San Francisco Bay-Delta
- Duck hunting started on natural ponds in the tidal marshlands
- Current landscape reflects changes made for a variety of reasons
- Understanding that history - from tidally open ponds to ponds mostly behind levees - can help understand current conditions and provide new management insight

Today's Suisun Marsh

This section consists of four main elements - general introduction to the marsh, physical and physical processes, water management infrastructure and biotic communities. This division is based loosely on the way in which topics were organized for the workshop.

Introduction

Laurie Briden's (DFG) introduction to Suisun Marsh forms the basis for this section. Figure 4 shows the marsh study/management area and its relation to Grizzly and Honker bays. Saltwater enters the marsh from the lower estuary though tidal action, and freshwater enters from the Sacramento and San Joaquin rivers to the east, from local streams and from the Fairfield Water Treatment Plant. Interaction of these seasonal and daily varying sources results in the brackish marsh with a variety of habitat types (Figure 5). The marsh contains both private and public lands (Figure 6) with the approximate split being 115,300 acres of private lands 52,000 acres of managed wetlands, 6,300 acres of tidal wetlands, 30,000 acres of bays and sloughs, and 27,000 acres of upland grassland) and 15,300 acres of public lands owned by DFG. Most lands are managed wetlands, i.e. the lands are isolated from tidal action by an extensive levee system.

Water management in the marsh consists of moving water from the channels to the leveed marsh lands through about 425 individual diversion structures (Figure 7). Fish protection requires that these diversions be screened or that the time when diversions can occur is limited. Figure 8 illustrates the amount of land that can be served by screened diversions.

The Suisun Marsh has several salt marsh harvest mouse (SMHM) conservation areas set aside in part to mitigate for effects of marsh management practices on the SMHM. Although not described specifically by Briden, the marsh is a permanent or temporary home for several listed species of plants and animals (Table 2). In addition to the listed species, there are more than two dozen plants and animals that are considered to be at risk and deserve special consideration when building facilities in the marsh and operating and maintaining existing facilities. There are several tidal wetlands restoration projects in the marsh (Figure 9). These projects are in part to help meet the CALFED goal of restoring 5,000 to 7,000 acres of tidal wetlands in the marsh.

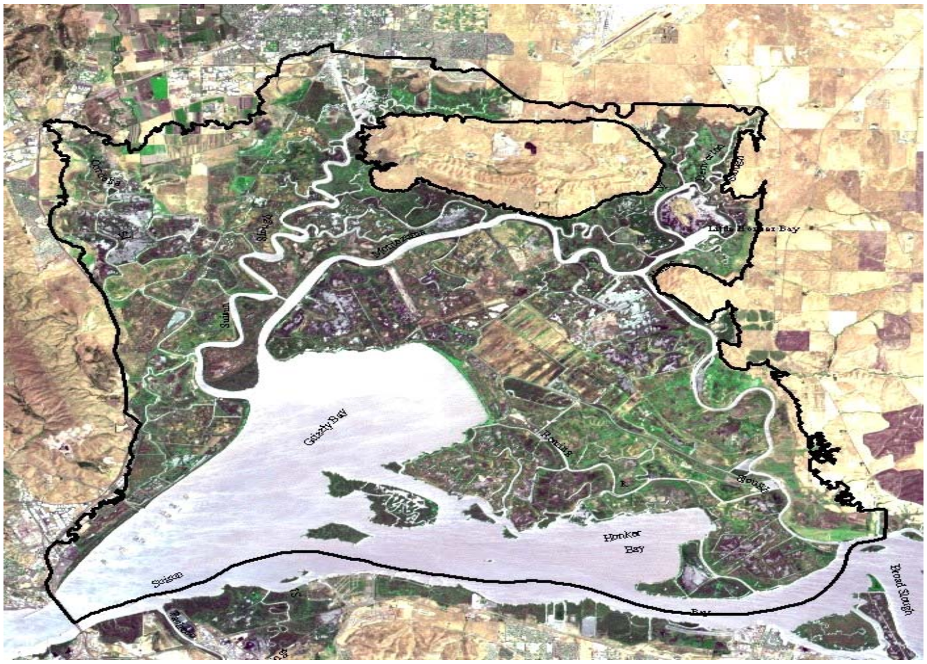


Figure 4. Suisun Marsh study area. (Source: L. Briden.)

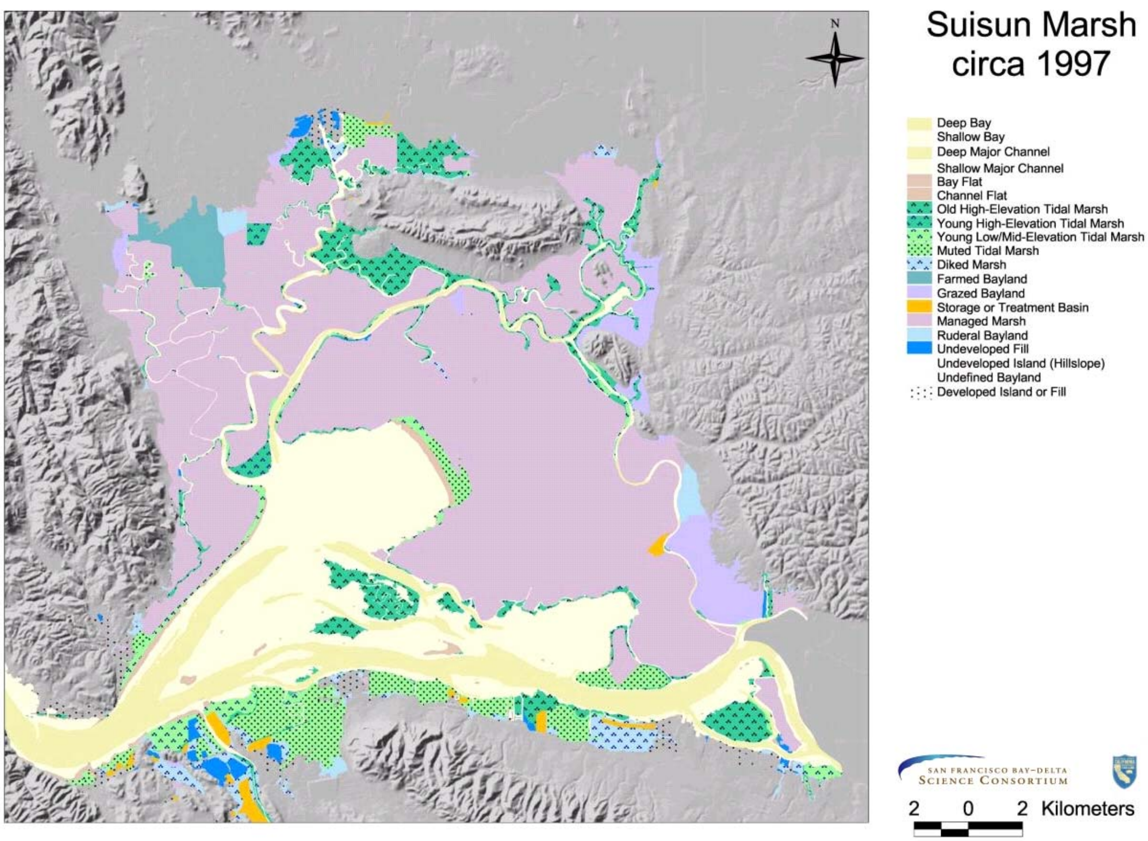


Figure 5. Various habitats in Suisun Marsh circa 1997. (Source: L. Briden.)

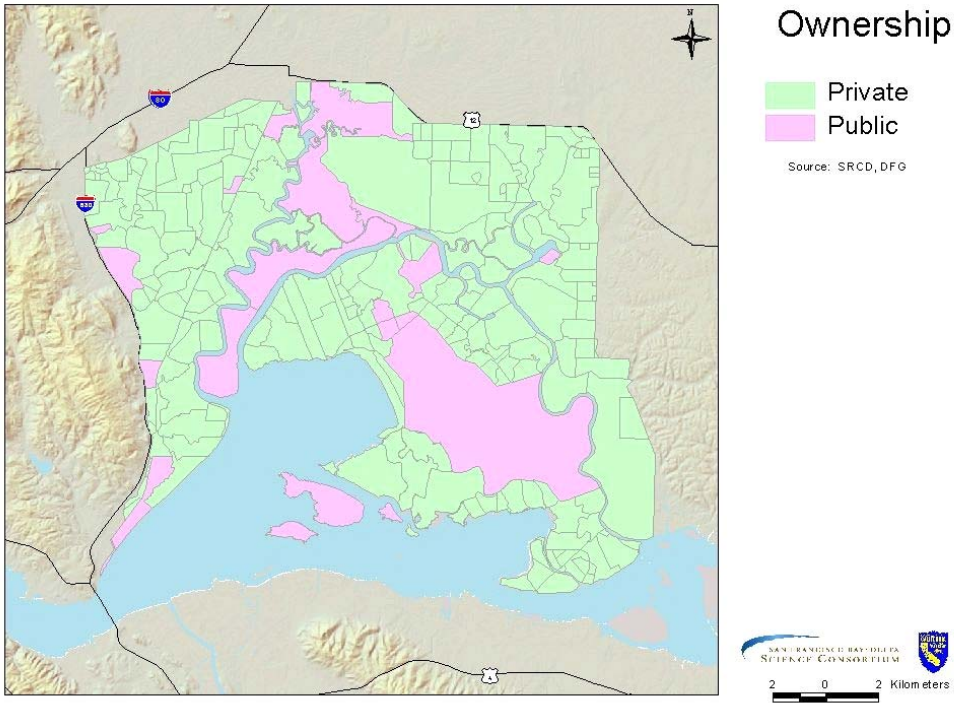


Figure 6. Land ownership in Suisun Marsh. (Source: L. Briden.)

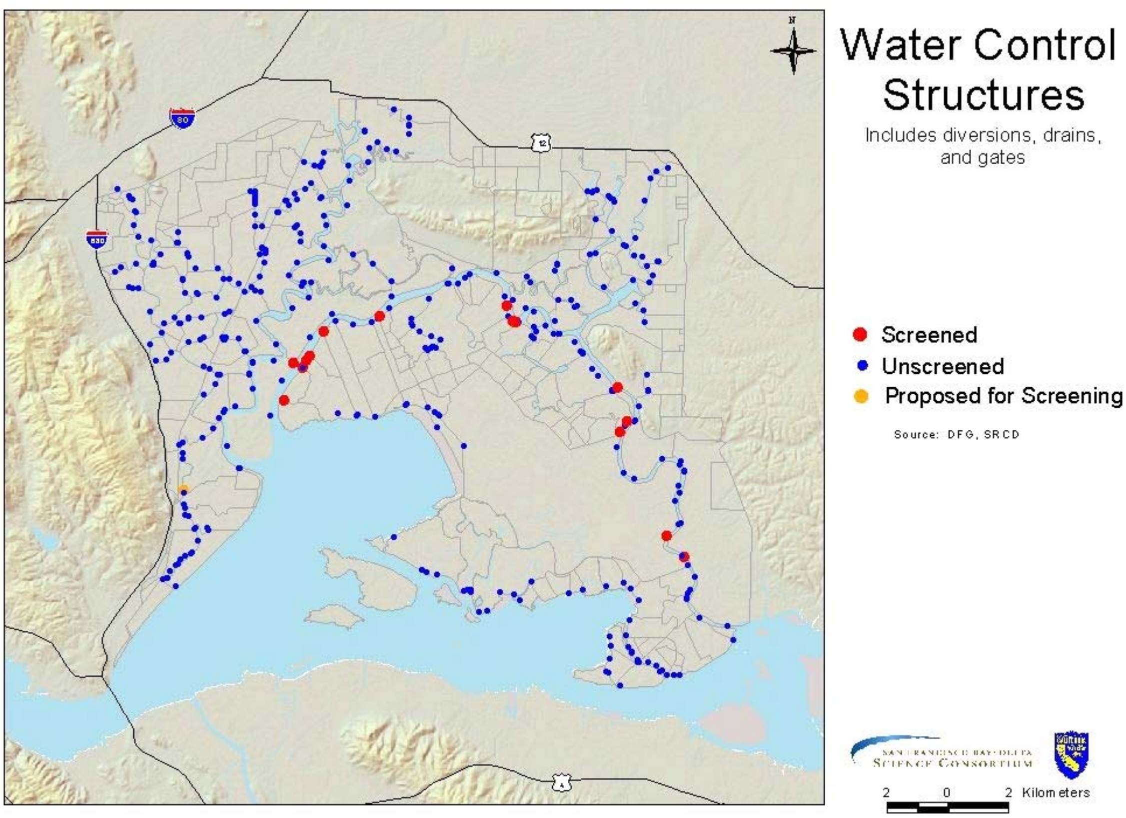


Figure 7. Water diversion structures in Suisun Marsh. (Source: L. Briden.)

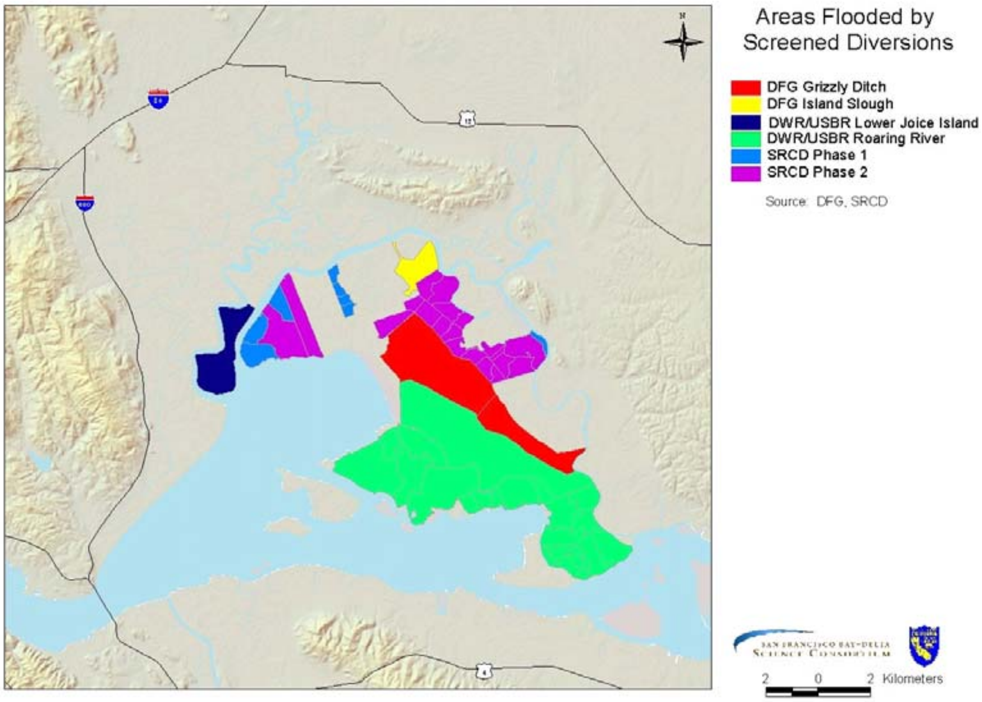


Figure 8. Areas in Suisun Marsh served by screened diversions. (Source: L. Briden.)

Table 2. Suisun Marsh plants and animals listed pursuant to either the federal or state endangered species acts

Common Name	*Listing Status*
Mammals	
Salt marsh harvest mouse	Endangered
Birds	
Aleutian Canada Goose	Threatened
Western snowy plover	Threatened
Bald eagle	Threatened
American peregrine falcon	Endangered
California clapper rail	Endangered
California least tern	Endangered
Fish	
delta smelt	Threatened
Central Valley steelhead	Threatened
Winter Chinook	Endangered
Spring Chinook	Threatened
Amphibians	
California red-legged frog	Threatened
Plants	
Suisun thistle	Endangered
Soft birds-beak	Endangered

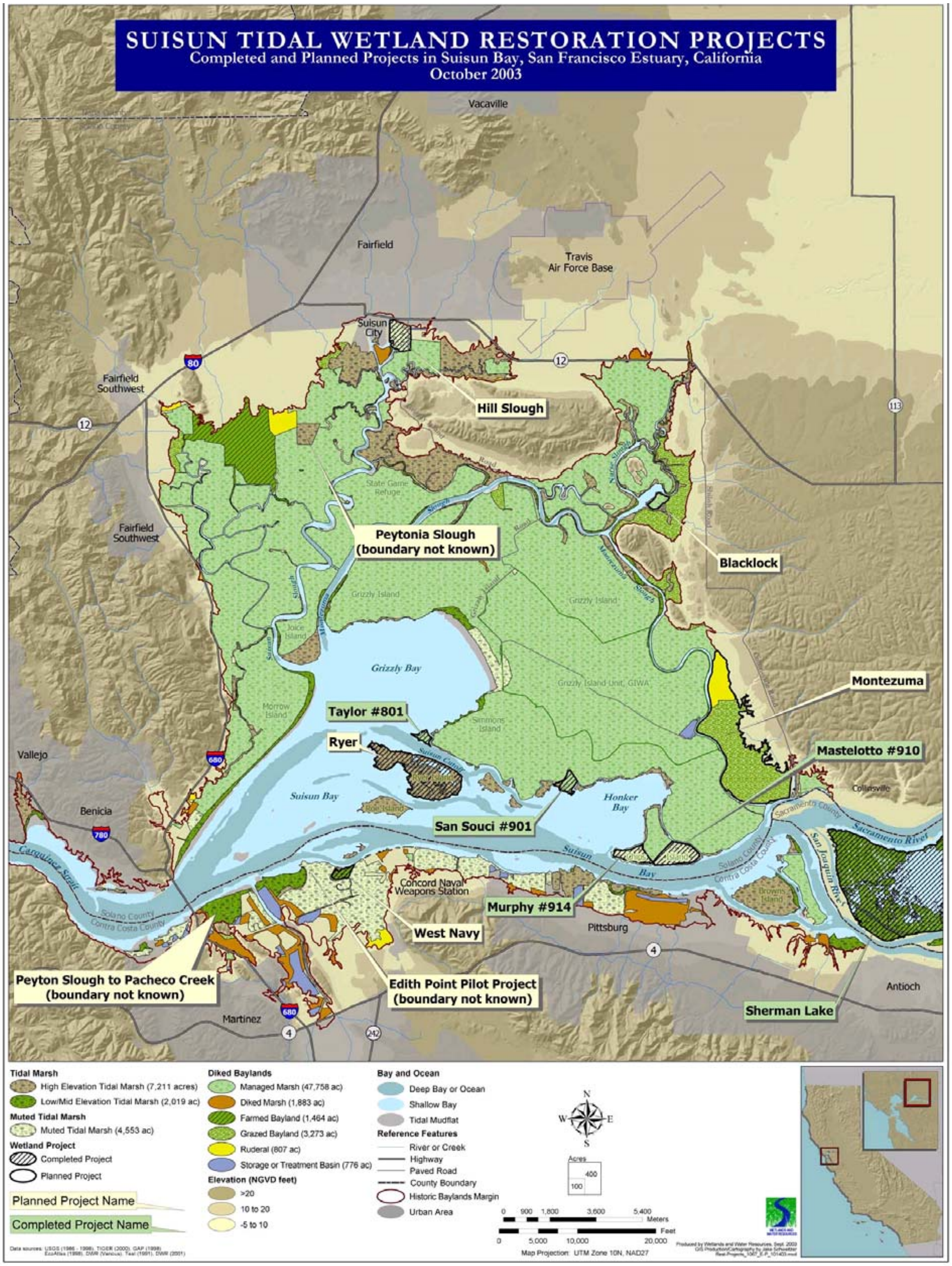


Figure 9. Suisun Marsh tidal wetlands projects. (Source: L. Briden.)

Briden's presentation demonstrated the complex nature of the marsh and the varied and valuable habitat within its boundaries. This habitat, and its wildlife populations attracts, on average, about 50,000 hunter days, 51,000 angler days and 18,000 miscellaneous visitor days (hiking, birding, nature watching, photography) each year. There are some outside constraints that may affect the marsh and its habitat, including:

- sea level rise (and climate change)
- proposed highway 680/80 bypass
- petroleum product transmission lines
- urban encroachment

Discussion of Introductory Session

Frank Wernette (DFG) facilitated a discussion among the audience and the introductory session speaker. The following are some of the major points I believe arose during the discussion. These points should be considered when thinking of modifying marsh landscape, changing management practices, and science needs in Suisun Marsh.

- Habitat goals may be in conflict - for example managed wetlands and restoration of ecological processes - and planners and managers must include conflict resolution in the planning and implementation processes.
- Managers and scientists should look at proposed actions in terms of information gaps - i.e. what information do we need to reliably predict the outcome of an action.
- There was a concern expressed by some members of the audience that tidal wetlands restoration could lead to less emphasis on water quality and less water quality monitoring. This concern should be addressed by the Charter marsh planning process.
- Any planning in the marsh must consider future conditions - e.g. water development upstream and climate change. Science must be an integral part of this examination.
- Planners must consider how landowners will be affected by plans to restore 5,000 - 7,000 acres of tidal wetlands in the marsh - i.e. about 10-15 percent of the total managed wetlands in the marsh. The effects of tidal wetlands restoration on the levees surrounding the remaining managed wetlands are of particular concern.
- Some attendees were concerned that restoration means trying to achieve pre-European conditions in the marsh. The general response was that getting back to 1850 is not possible, or perhaps even desirable. Restoration should be thought more in terms of re-creation - i.e., some lands now behind levees will be open to tidal action. The conceptual model (hypothesis) is that these areas will provide important habitat for native animals and plants; habitat that has been mostly lost over the past 150 years.
- Marsh managers and planners need to consider how the small streams flowing into the marsh fit into the overall marsh physical and biological functions. The wastewater treatment plant should also be included as a significant input to the marsh.
- Marsh managers should consider an experimental approach to marsh planning - perhaps small studies in small area over a long period. They should not rush into large actions without better information

- Landowners are concerned about urban encroachment. They hope to continue hunting clubs and to maintain waterfowl habitat in the midst of subdivisions that are popping up around the marsh. The landowners present at the workshop also recognized that the marsh and the rest of the estuary are closely linked and need to be examined collectively, not as separate entities.

Physical Processes

This section includes salt and particle transport, long-term salinity trends in Suisun Marsh and Suisun Bay, sediment supply, geomorphic processes as they relate to ecosystem function, and dissolved organic carbon. As will become apparent, we have relatively little data from the marsh on these topics - with most of the information coming from studies in the Delta, the northern estuary, and similar marshes in the estuary. One of the conclusions from the presentations is that more studies in the marsh are needed before scientists and managers can develop useful conceptual models of marsh processes.

Transport of Salt and Particles Within Suisun Marsh and In and Out of Suisun Marsh

I am grateful to Jon Burau of the USGS for providing excellent notes from his presentation: on transport entitled “Transport in Suisun Marsh - Why Do We Care and What Do We Know?” I have included his notes below with minor editorial changes. Understanding the movement of salt and particles within in the marsh is critical to our understanding of the marsh and its connection to the estuary.

Why Do We Care? Transport processes in Suisun Marsh channels are primarily driven by the tides and thus are extremely dynamic. Transport is the movement of dissolved and particulate constituents, “stuff,” in the water column from place to place. It is well known that water moves from place to place, or is transported, within the network of channels that make up Suisun marsh. But “stuff” in the water is also moved from place to place by the tides, sometimes non-intuitively. Stuff can be dissolved minerals (salt), constituents important for drinking water (such as bromides and trihalomethane precursors), pollutants (such as pesticides, herbicides, mercury, and selenium), and biota (such as bacteria, phytoplankton, zooplankton and fish early life stages). All of these fundamental ecosystem quantities are exchanged between the marsh, the surrounding uplands, and the greater Bay-Delta system. These materials are moved about and mixed within the marsh as well.

What Do We Know in General? Three fundamental mechanisms control transport in estuaries in general, and in Suisun Marsh in particular. These mechanisms are: (1) advection, (2) dispersion, and (3) gravitational circulation.

Advection is the movement of constituents with the currents. The track of a single particle (as modeled by following neutrally buoyant drifters released at various locations in the marsh or estuary) over a flood or ebb cycle provides a good representation of the advective transport of a water parcel by the tidal currents. In the context of the longer term (>24 hours) movement of constituents, it is most useful, however, to think of advection in terms of net currents, i.e. net movement over more than one tidal cycle. In the case of Suisun Marsh, advective processes are driven by local hydrologic inputs such as river and creek inputs, sewage discharge and the operation of the Suisun Marsh Salinity Control Gates (SMSCG) - all of which significantly vary at seasonal timescales.

Dispersion is transport due to mixing. In the context of the channel network that makes up Suisun Marsh, long-term (>24 hrs) dispersion transport is primarily caused by the mixing of water at channel junctions. Although lateral-shear-induced mixing can occur within the wider channels, such as in Montezuma and Suisun Sloughs in the south-western marsh, the contribution of this mixing process is unknown. Moreover, we don't know how secondary circulation in the bends of the hugely sinuous sections of Suisun Slough contributes to dispersive transport. Nonetheless, at junctions the water from different areas of the marsh meet, often containing dissimilar constituent loads, and mix. The divergence (spread) of a group of proximately released drifters is a reasonable way of visualizing dispersive transport. Large dispersive transport of a constituent past a given point is characterized by higher concentrations on one tidal phase as compared to the other tidal phase. For example, if the concentration of larval fishes were greater in Hunters Cut on flood tides over ebbs, we would say that fish were being transported from Montezuma Slough through Hunters Cut into Suisun Slough due to dispersive transport mechanisms.

Gravitational circulation is a horizontal density gradient driven exchange flow that brings salty water landward at the estuary bottom and a fresh water return flow at the surface. Gravitation circulation typically occurs when a horizontal salinity gradient exists in areas with deeper channels that have relatively weak tidal currents. For example, strong gravitational circulation has been measured in the Carquinez Strait. Weak gravitational circulation, apparently modulated by SMSCG operation, was measured in Montezuma Slough near its connection to Grizzly Bay in 1999. Overall, however, gravitational circulation is likely to be a relatively minor transport mechanism in Suisun Marsh compared to dispersive and advective mechanisms, particularly when the salinity control gates are operating.

What do we know in Suisun Marsh? Aside from what we have learned from one dimension numerical model experiments, we know very little about transport in Suisun Marsh. The models have not been calibrated against flow data collected in the marsh, because virtually none exist. With the lack of model-data comparisons (model verification), it is unclear how well the numerical models work in the marsh.

In general, transport evolves from the interaction between two basic factors: (1) geometry, and (2) forcing mechanisms. Suisun Marsh's geometry is characterized by a network of channels dominated by Montezuma Slough and Suisun Slough. Secondary channels, such as Nurse Slough and Hunters Cut are also important. Interestingly, Suisun Slough south of Hunters Cut appears to be filling in with sediment because most of the tidal exchange to the upper reaches of Suisun Slough appears to be carried by Hunters Cut. Suisun Marsh has two major connections to the estuary: (1) where Montezuma Slough connects to Grizzly Bay to the west and (2) the Montezuma Slough connection with the Sacramento River, near Chain Island, to the east.

Forcing mechanisms in Suisun Marsh include (given in descending order of overall importance): (1) tides, (2) hydrology, (3) salinity control gate operation, (4) meteorological effects, (5) salinity, (6) duck club operations, (7) marsh exchange processes. The tidal flows in the Suisun Marsh area are large and vary throughout the marsh. For example, the tidal flows in Carquinez Strait are on the order of +- 600,000 cubic feet per second (cfs), at Chipp's Island they are roughly +-300,000 cfs. Tidal exchange into Suisun Marsh through the west end of Montezuma Slough is +-50,000 cfs, whereas, the tidal flows within Montezuma Slough's west end are on the order of +-6,500 cfs. Within the marsh, the only tidal exchanges that have been measured are in Hunters Cut, where the flows were on the order of +-12,000 cfs. This may seem like a insignificant amount when compared to Carquinez Strait, however, since Hunters Cut is only about 60 feet wide, the resulting currents can be strong - with peak currents at about 3 feet per second, or about the same current speed as is observed in Carquinez Strait. Overall, the tidal forcing varies considerably from the west, where it is stronger, to east, where it is weaker and where the influence of the river inputs within the Delta are more pronounced. And, in general, the influence of the tides on transport also decreases from south to north.

The relatively large tidal flows in the marsh lead to comparatively large current speeds, which in turn means individual water parcels can travel long distances over a half tidal cycle (approx. 6 hours). For example, within the estuary, drifters released on an ebb tide near the Benicia Bridge traveled all the way into Suisun Cutoff, a distance of approximately 8 miles. This is a long distance when you consider Suisun Bay itself is only about 12 miles long. Within the marsh, water parcels also travel long distances. For example, drifters released at the north end of Cutoff Slough on an ebb tide travel nearly to Hunters Cut, a distance of about 4.5 miles. On the same tide, drifters released at the east end of Cutoff Slough traveled roughly 6 miles, all the way into Grizzly Bay on a single ebb tide. Moreover, drifters initially released within 50 feet of each other within a channel can end up miles apart after a single tide because of the dispersive mixing processes discussed above.

The net (or residual) flows can also influence transport in the marsh by pure advection (see above). In the case of the net flows, the SMSCG, when it is operating, is the single biggest factor. Under "full bore" operation the control gates introduce a net flow from east to west of about 3,000 cfs. The hydrologic inputs from the creeks that border Suisun Marsh, and the Fairfield/Suisun treatment plant, also create net flows in the marsh, although, with the exception of the treatment plant flows, these inputs vary seasonally. For example, Green Valley Creek has an average annual discharge of 12 cfs, but can have peak discharges, from rainfall runoff, exceeding 5,000 cfs. By comparison, the Fairfield Suisun Treatment Plant has a relatively stable discharge of 6-12 cfs. Finally, again with the exception of the treatment plant, these hydrologic inputs, essentially the connection of the marsh to its uplands, are virtually unknown.

Burau concluded that:

- Transport in Suisun Marsh results from a variety of forcing mechanisms that interact within a channel network.
- In general, transport is dynamic and, to a large extent, is driven by the tides.
- Hydrodynamic and hydrologic data in the marsh are sparse.

Long-term Salinity Trends in Suisun Bay and Suisun Marsh

One of the original paradigms in the Suisun Marsh management conceptual model was that bringing the State Water Project on line in the late 1960s, along with the already operating Central Valley Project, would dramatically reduce Delta outflow and increase salinities in marsh channels. In his workshop presentation Chris Enright of DWR looked at long-term salinity trends in the marsh and Suisun Bay to determine if this paradigm had proven to be accurate. He also examined the effects of the salinity control gate operation on salinity in Montezuma Slough. The following is based on his presentation.

For his analyses Enright used salinity data from three stations:

- Port Chicago (since 1947)
- Beldons Landing (since 1929)
- Collinsville (since 1920)

The sample frequency and methods varied between grab samples collected every four days (through 1971) and continuous measurements of specific conductance after 1967 - thus there was a four year overlap in measurement techniques. Enright developed relationships to convert total dissolved solids to specific conductance and to extrapolate from high tide samples to monthly averages. He also used calculated daily outflow from DWR's DAYFLOW program and a watershed precipitation index derived from 13 stations around the San Francisco Estuary watershed.

The resulting salinity records at the three Suisun Marsh related stations and the Delta outflow/project pumping records are shown in Figure 10. Using statistical techniques to detect any trends in the data, Enright concluded that:

- Watershed precipitation has increased about 0.06 inches per year since 1920 (p+0.3). During the pre-project period, outflow has a positive trend (in concordance with precipitation) but a negative trend since the 1960s (opposite from the precipitation trend). On a monthly time scale, the precipitation index does not exhibit a trend.
- Salinity is negatively correlated with outflow, except at Beldons Landing and has significantly decreased during the post-project period.
- As expected water project operations have caused negative outflow trends in April, May and June and positive outflow trends in July, August and September.
- Despite the variability-reducing impacts of water project operations on outflow (reduced in spring and increased in summer), variability in salinity and outflow are greater in the post-project period as compared to the pre-project period. This high variability demonstrates the importance of annual climate variability on salinity and outflow trends.
- When operated as a tidal pump, the SMSCG reduces salinity across the Suisun Marsh between 8 mmho/cm (in the eastern marsh) and 1mmho/cm (in the western marsh). Among-month trends at Beldons Landing are slight and insignificant in the pre-SMSCG period (1921-1987) except in September and October, which exhibit negative trends. Trends in all months decrease in the post-SMSCG period - a result of the effectiveness of gate operation and the early dry and later wet year sequence since 1988. Overall the SMSCG has likely reduced Suisun Marsh salinity significantly more than it would have been increased without the facility but with increased project exports.

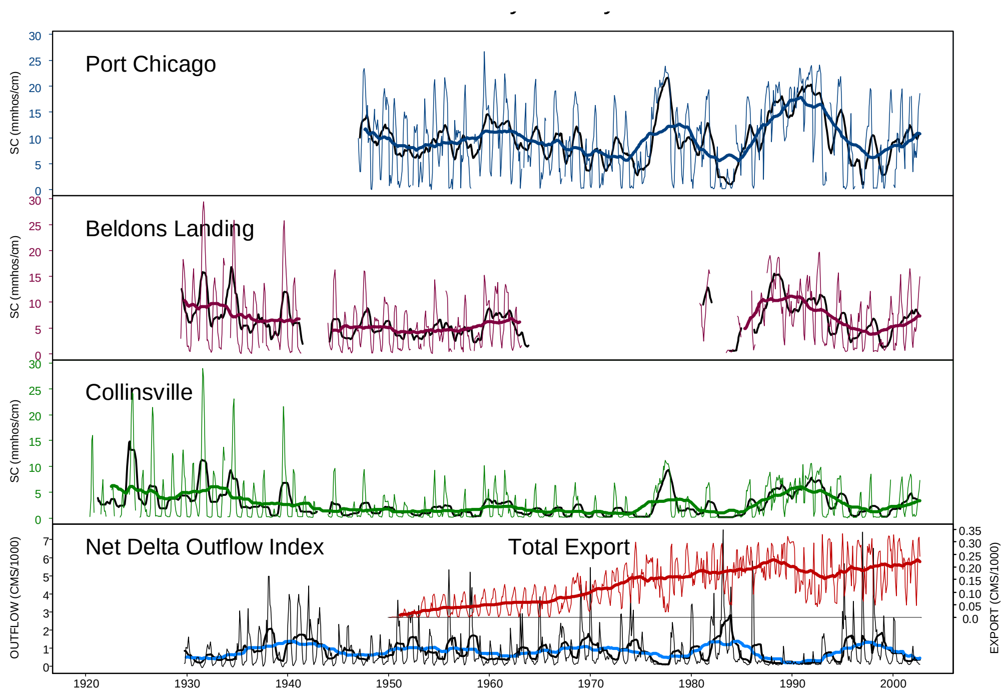


Figure 10. Long-term Suisun Marsh and Suisun Bay salinity trends, net Delta outflow index, and CVP and SWP exports from 1920-2002. (Source: C. Enright.)

Lessons Learned from Other Systems: Sediment, Mixing, Transparency

Dave Schoellhamer (USGS) reported on studies from other local systems that may help understand and manage Suisun Marsh. He emphasized that the local studies are ones in which he has been involved but his presentation was not a comprehensive review of all studies and their results. He has not been part of any specific studies in Suisun Marsh, and he not aware of any studies that bore directly on questions related to sediment dynamics in the marsh.

Montezuma Slough (and Suisun Marsh) has two entrances - one on the east and one on the west. This two-entrance configuration is similar to that found in the Napa-Sonoma Marsh where tides propagate into the marsh from both ends through a series of sloughs, and converge in center of marsh, at the barotropic convergence. At the convergence there are slow currents, sediment trapping and deposition, and long residence times. The long residence time at the barotropic convergence can also cause salt trapping. For example during a levee breach in the Napa-Sonoma Marsh, salty water moved out of a pond into a slough and was transported within the system. Within a few days salinity increased and remained high for several days at the barotrophic convergence zone due to trapping process. This demonstrates the importance of the convergent zone in two entrance systems.

Another similarity between Suisun and the Napa-Sonoma marshes are physical controls at the entrance to the main channel entering the marshes. In Suisun Marsh, during parts of the year, the SMSCG control flow and have large effects within the system - for example, during the spring tides the gates cause the tides to be truncated. With the gates operating, the net tidal flow in Montezuma Slough is from east to west In the Napa-Sonoma Marsh, the Sonoma Creek sill causes similar tidal truncation, and the average net flow in the marsh complex is from east to west.

Dead end channels, a prominent feature of Suisun Marsh, are also found in other local marsh systems. During the dry season, dead end channels with no freshwater inflow, can become isolated. For example, in the Petaluma River, as water moved out of the river into to San Pablo Bay, tidal energy did not move sediment to San Pablo Bay, so it became trapped in the dead end channels. The trapped sediment had high mercury concentrations, with the mercury in every sample collected exceeding water quality guidelines. In another example of problems caused by dead end channels, this one from Cape Coral in Florida, poor circulation in a residential canal system caused water quality problems. Although tide gates, such as the SMSCG, may help circulation in dead end channels, the channels do not flush well and will remain a challenge.

The large surface area of Suisun Marsh relative to Suisun Bay has geomorphologic implications if the physical configuration is changed - e.g. by creating more tidal wetlands. In the South San Francisco Bay salt ponds, numerical modeling indicates that restored Alviso ponds will increase tidal prism and trap sediment. Opening the ponds and changing the tidal prism can also affect phytoplankton blooms through changes in pond turbidity. For example clearing rates (sediment dropping out of water column) can increase significantly when ponds are opened (and water velocities decrease) and the region can move from not supporting algal blooms to where they are supported.

A summary of lessons from similar systems:

- Barotrophic convergence can occur in two entrance systems
- System is controlled by entrance boundary condition and dead end channels are isolated
- Large surface area and tidal prism can affect system geomorphology and ecology.

- Numerical models may help conceptualize the consequences of different management options, including installing tidal gates and levee breaches.
- Although the results from similar systems can provide useful information, specific interdisciplinary studies are needed in Suisun Marsh.

Suisun Marsh Geomorphologic Process, Ecosystem Function, and Contemporary Management Practices

The following material is from the workshop presentation of the above title by Steve Culberson of DWR. Culberson divided his presentation into three parts - a description of some basic geomorphologic processes in Suisun Marsh and the estuary and how these processes may have been disrupted by management practices in the marsh and other portions of the estuary, a conceptual model that emerges from the processes, and finally, some ideas about science needs in the Suisun Marsh. In this section, the material is restricted to the basic geomorphologic concepts. Culberson's conceptual model is discussed in the section that reviews several marsh-related models, and his thoughts on the science agenda are included in the final section of this report.

Culberson started the presentation with two messages he hoped the workshop participants would take from his talk, namely:

1. Recent (1850s to date) historical land use practices of diking, draining, farming, and seasonally managing Suisun Marsh tidal wetlands have altered or removed the geomorphologic processes which create and maintain tidal marsh landscapes in the San Francisco Estuary.
2. Reduction of vascular plant primary productivity and reduced storage and/or oxidation of fixed organic carbon within Estuary's tidal marshes has occurred coincidentally with a decline in Suisun Marsh and San Francisco Estuary biological abundance, resilience, and diversity.

Geomorphology is the study of landforms and the processes that make them. Biogeomorphology considers the specific role of plants and animals in geomorphologic processes. A combination of physical and biological processes caused the estuary to take on the configuration shown in Figure 11. The tides (a function of the ocean, sun, moon, bathymetry, meteorology and climate) and accretion through sediment supply and disposition, and organic matter accumulation all interact to determine the composition of marsh soils and intertidal elevations.

Culberson advanced the following supposition and its corollary regarding tidal marshes in the San Francisco Estuary:

Supposition. Tidal marshes of the San Francisco Estuary occur at the interface of, and as the result of, interactions between a largely physical system (tides) and a largely biological system (vegetation distribution and productivity).

Supposition Corollary. Physical system and biological system elements are necessary for the existence and maintenance of tidal marshes in the Estuary, and geographical gradients exist over which the strength of individual system elements vary.

Removal of free tidal access in managed marsh wetlands has resulted in 1 to 3 feet of subsidence on lands behind the levees. Management practices such as tilling, drying, burning of vegetation (and soils) have resulted in additional subsidence. On top of this, sea level rise of the last century has increased the water elevation on the bay side of marsh levees. These marsh activities have been on top of other human induced changes in inorganic sediment supply to the estuary (Figure 12).

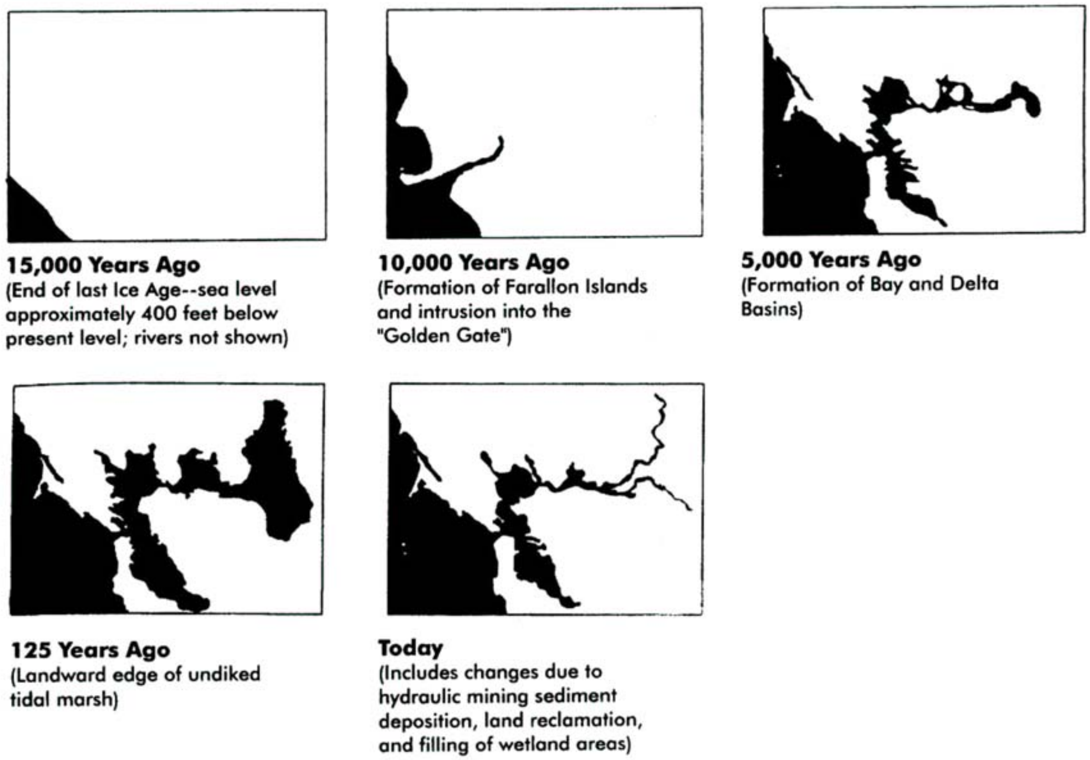


Figure 11. Sea level in the San Francisco Estuary for the past 15,000 years. (Source: S. Culberson.)

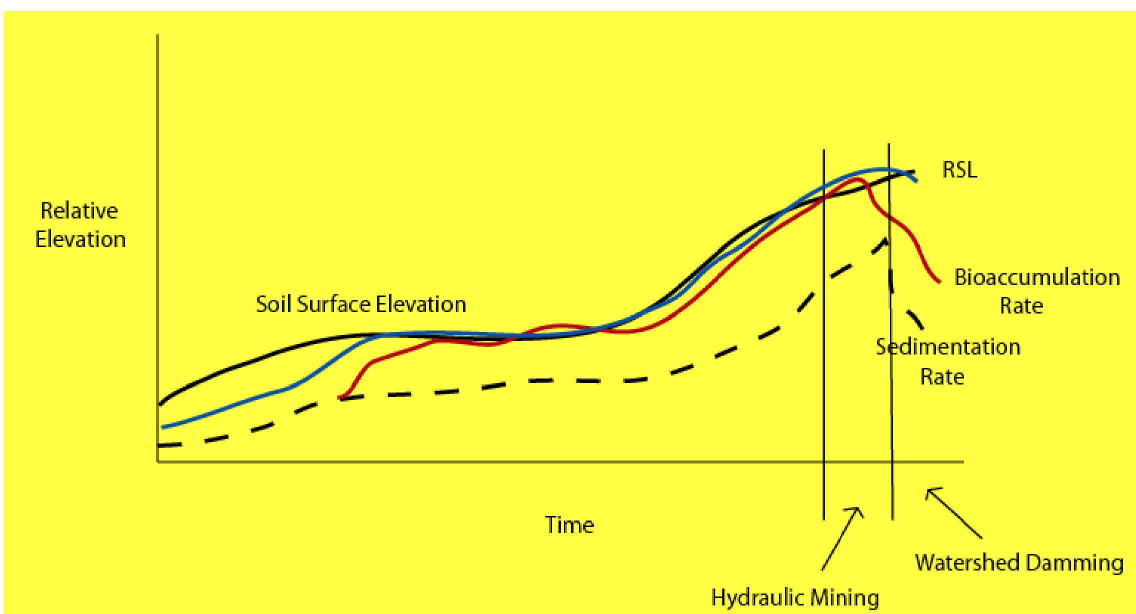


Figure 12. Conceptual model of historic soil formation patterns in the San Francisco Estuary. (Source: S. Culberson.)

The following contemporary management practices have affected rate of subsidence and thus land surface elevation behind the levees:

- maintaining levee and water conveyance structures,
- maintaining drainage and leaching capabilities,
- establishing local brood ponds,
- maximizing waterfowl-appropriate vegetation, and
- annual maintenance and weed control have resulted in the following consequences:
  - – drying of surface soil horizons,
  - – oxidation of surface soil organic material,
  - – reduction of available soil pore water and plant productivity,
  - – local hypersalinity/acid leachates,
  - – attenuation of biomass/carbon production and storage, and
  - – subsidence.

The consequences of historic and possible future marsh management scenarios are illustrated in Figures 13 and 14. We have a "natural" experiment in the Delta (Figure 15) which shows the outcome of management on reclaimed Delta lands.

Culberson speculated that the loss of stored primary productivity in the form of sequestered plant biomass may be one of the causes of biological productivity declines in San Francisco Estuary and asked if we have isolated Suisun (and Delta) ecosystem carbon cycling functions to the detriment of the regional ecosystem?

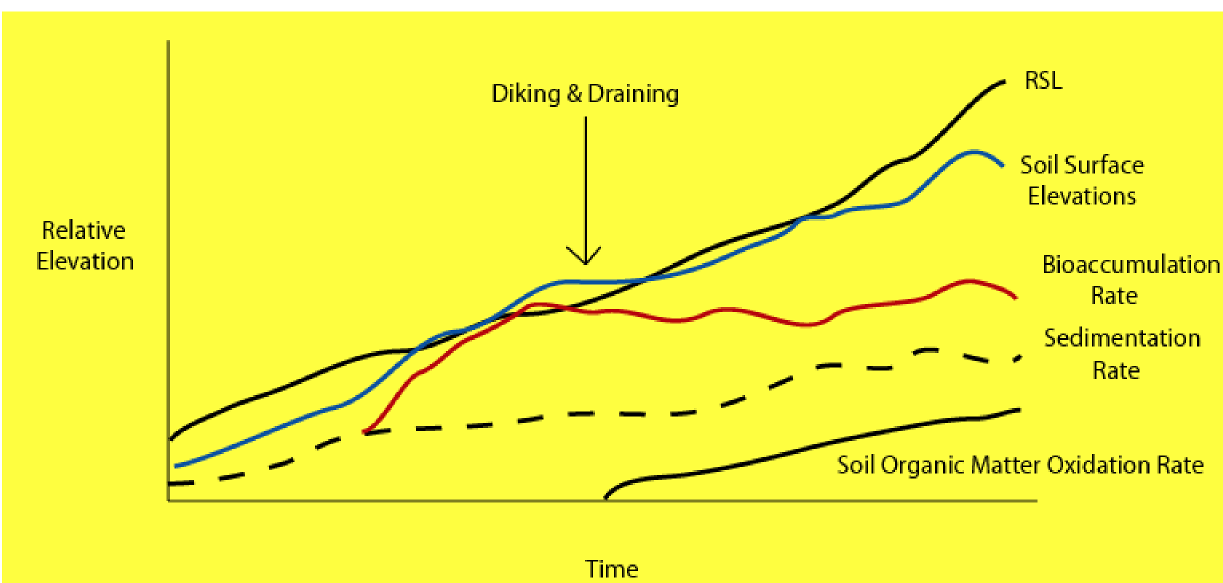


Figure 13. Contemporary soil formation in Suisun Marsh. (Source: S. Culberson.)

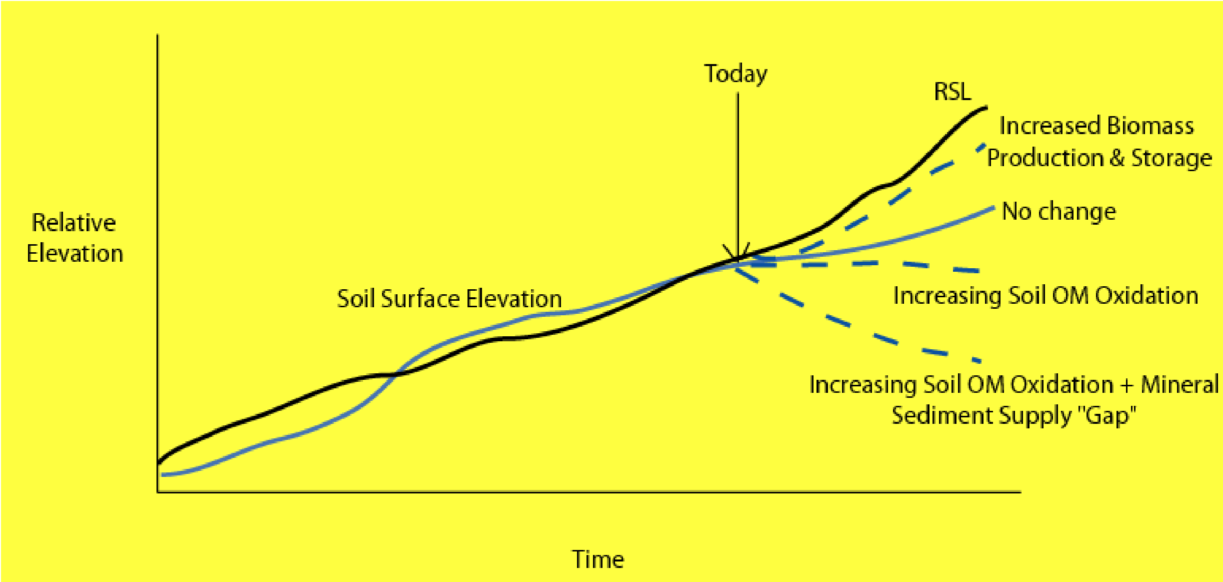


Figure 14. Possible future soil formation scenarios in Suisun Marsh. (Source: S. Culberson.)

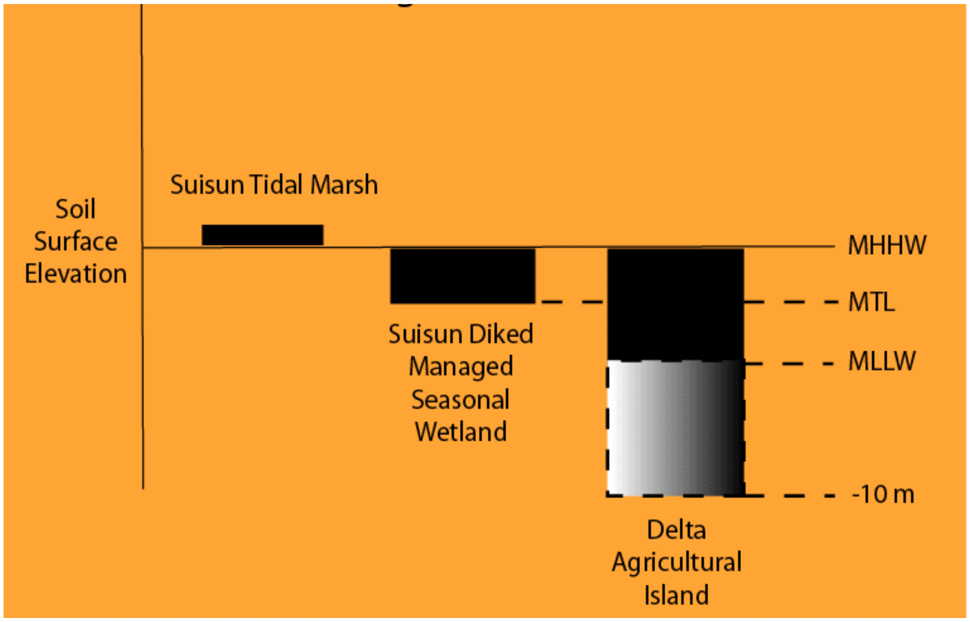


Figure 15. Comparative analysis of management regimes on existing soil surface elevations in the northern San Francisco Estuary – a natural experiment. (Source: S. Culberson.)

He suggested that management direction move towards a more natural template and at the ecosystem and landscape levels. Biogeomorphologic restoration would involve maximizing plant biomass productivity using vegetation communities adapted to ambient (historical) tidal regimes and salinities, and maximizing in situ storage of organic matter and contributions to soil horizons. In other words,

a. Let nature produce the carbon.

b. Let nature bury the carbon.

c. Leave the buried carbon alone.

Organic Carbon Contribution from Wetlands

Organic carbon, both particulate and dissolved, poses a bit of a dilemma for the CALFED program and stakeholders with an interest in estuarine restoration and the Delta as a water supply for millions of Californians. On one hand, organic carbon (resulting from the production and decomposition of plants and animals in the estuary and upstream0 is an important component of the estuarine food web. On the other hand, the combination of a disinfectant (chlorine) and dissolved organic carbon in a water treatment plant can result in the formation of trihalomethanes - compounds that have potential carcinogenic properties. Jassby and Cloern (2000) examined the sources of organic carbon entering and produced in the San Francisco Estuary and concluded, among other things that tributary inflow was the major source of organic carbon to the system and that organic carbon in drainage from tidal wetlands was a tertiary source. They did speculate that proposed restoration (and rehabilitation) actions proposed by CALFED and other had the potential to change the carbon budget.

Roger Fujii (USGS) reported on three studies of sites in the Delta and Suisun Bay that can provide some information three potential sources of carbon to the estuary. Fujii emphasized that he had no specific data on Suisun Marsh nor was he aware of any.

The three studies described by Fujii were undertaken to answer the question posed to CAlFED in 1998:

> *What are the loads of DOC and trihalomethane (THMP) precursors produced by agricultural operations, constructed wetlands, and tidal wetlands?*

The studies designed to answer that question have been underway for several years and are:

1. Two agricultural fields on Twitchell Island

   – Twitchell South (TS), southern field, higher Soluble Organic Matter (SOM)

   – Twitchell North (TN), northern field, lower SOM, soils similar to wetland

2. Constructed Wetland on Twitchell Island (for subsidence mitigation and reversal)

   – Adjacent to TN, similar soils, flooded Sept. 1997

   – Continuously flooded to 50 cm (east pond)

3. Tidal Wetland - Browns Island, a 595-acre island located near the junction of the Sacramento and San Joaquin rivers north of the city of Pittsburg.

Fujii described the field and analytical methods used to estimate carbon source data summarized in Table 3.

Table 3. Preliminary estimates of carbon added from major Delta sources

Source	*Fractional Area*	*Export Production*	*Fractional DOM Contribution*
Algal	15%	7-14 gC/m^2-yr (10% of PP, Jassby et al. 2002)	7-12%
Ag Ops	80%	3-12 gC/m^2-yr (Deverel et al. in prep)	27-55%
Wetland[a]	5%	80-400 gC/m2-yr	43-68%

a. Twitchell constructed wetland: 105 gC/m2-yr

The limited information to date indicates that wetlands appear to supply a significant fraction of DOC added entering the Delta. The work at Browns Island and the agricultural and constructed wetlands sites also demonstrated the importance of getting the flows correct. The flows, and carbon fluxes, have considerable daily, seasonal and interannual variability and must be accounted for in the experimental design. It also important to begin studies in Suisun Marsh to determine if the marsh is a net carbon source or sink.

Discussion of Physical Processes

Zach Hymanson (CBDA) moderated the discussion following the physical processes talks. I follow the template initiated in the discussion at the end of the introductory session, that is, the following are major points arising during the discussion and question and answers among the participants and speakers.

- Subsidence in the marsh is important. Groundwater may be affecting subsidence but we are not sure. Land management practices on duck clubs include soil tillage, which generally increases subsidence. The elevation data base in the marsh is relatively weak and needs to be improved if we want to be able to accurately track subsidence.
- Heavy metals and other contaminants are a concern in the marsh but we don't have a lot of information
- Climate change, sea level rise and subsidence all point to the immediate need for inclusion of these concepts in the marsh planning process.
- Managers, planners and scientists must consider the range of marsh uses - e.g., tidal marshes, seasonal wetlands, and water quality - in developing an implementation strategy for the marsh.
- Some key marsh components - e.g. organic carbon fluxes at the marsh boundaries - are missing from the existing Suisun Marsh information base. The carbon question is complicated by its dual role as part of the estuarine food web (positive) and as a drinking water quality concern (negative). Recent modeling results have demonstrated the close link between what happens in the marsh, in the Delta, and in the San Francisco Estuary.
- Scientists and managers must consider the overall temporal and spatial scale in the marsh and the estuary. The system is very dynamic and studies and planning must encompass temporal scales ranging from daily tidal cycles to monthly, seasonal, and annual time frames.
- There is considerable value in using conceptual models when thinking about goals in the marsh, as well as in developing a marsh science agenda.

- On one hand it is technically possible to maintain marsh levees. On the other hand, levee maintenance is expensive and continuous. Consideration of the technical feasibility and costs of long-term levee maintenance must be part of any marsh implementation plan.
- Sediment and organic carbon are key factors in determining soil surface elevation of newly restored tidal marshes. We have little data on either of these components.
- Instead of focusing on the number of acres of tidal wetlands to be restored, perhaps we should focus on restoring functional processes in the marsh.
- Tidal marsh restoration (re-creation) will be on lands from willing sellers.
- There are numerous listed species in the marsh. These species need to be protected now. At the same time, researchers should investigate the habitat needs of these species and, as we learn more, recovery and protection actions can be modified.
- Adaptive management, either active or passive, should be an integral part of the marsh planning process.

Water Management Infrastructure

This description is restricted to the major facilities constructed with funding provided by DWR and the USBR during since the 1970s and taken mostly from the presentation by Victor Pacheco of DWR.

The water management infrastructure in the Suisun Marsh has generally been developed to provide water of adequate salinity and quantity to private duck clubs and public wetlands. Water management is influenced by a variety of goals and physical and administrative constraints such as individual club management plans (described later), water quality, tides, Delta outflow, condition of the intake structures, and any seasonal restrictions on diverting water from unscreened diversions. The marsh lands are at an elevation at or below mean sea level, thus the more than 400 flood/drain structures in Suisun Marsh rely mostly on gravity to fill and drain the flooded lands. The ability to fill and gravity depends on water level, which is strongly influenced by the constantly varying tidal stage. Storms can result in higher stage and limit the ability to drain the ponds. Intakes, drains, pipes and interior distribution system are all essential components of the infrastructure. Corrosion in the brackish water, sedimentation, and trash buildup at the intakes are continuing maintenance challenges.

Some intakes are screened to keep at risk and listed fish from being entrained. For unscreened diversions, there are restrictions as to when they can be operated. For example, salmon protection measures call for water intake through unscreened diversions to be limited to 25% of capacity from November 1 through the end of the duck hunting season and no diversions from February 21 through March 31. The screened diversions may have different approach velocity requirements (flow/screen area) during different portions to the year, depending on which species is present. For example, delta smelt require 0.2 fps, whereas salmon criteria allow 0.33 fps. Fish screens are costly, with high design and construction costs and often significant annual maintenance costs to keep the screens operating within design criteria.

As shown in Figure 16, there are 16 continuous monitoring stations scattered throughout the marsh to keep track of stage and salinity, as well as 5 compliance stations and 2 control stations. During the October through May control season, data from these stations are used to confirm compliance with SWRCB D-1485 water quality standards, satisfy Suisun Marsh Preservation Agreement requirements, manage salinity in the marsh, and trigger operation of the Suisun Marsh Salinity Control Gates (SMSCG, described later in more detail).

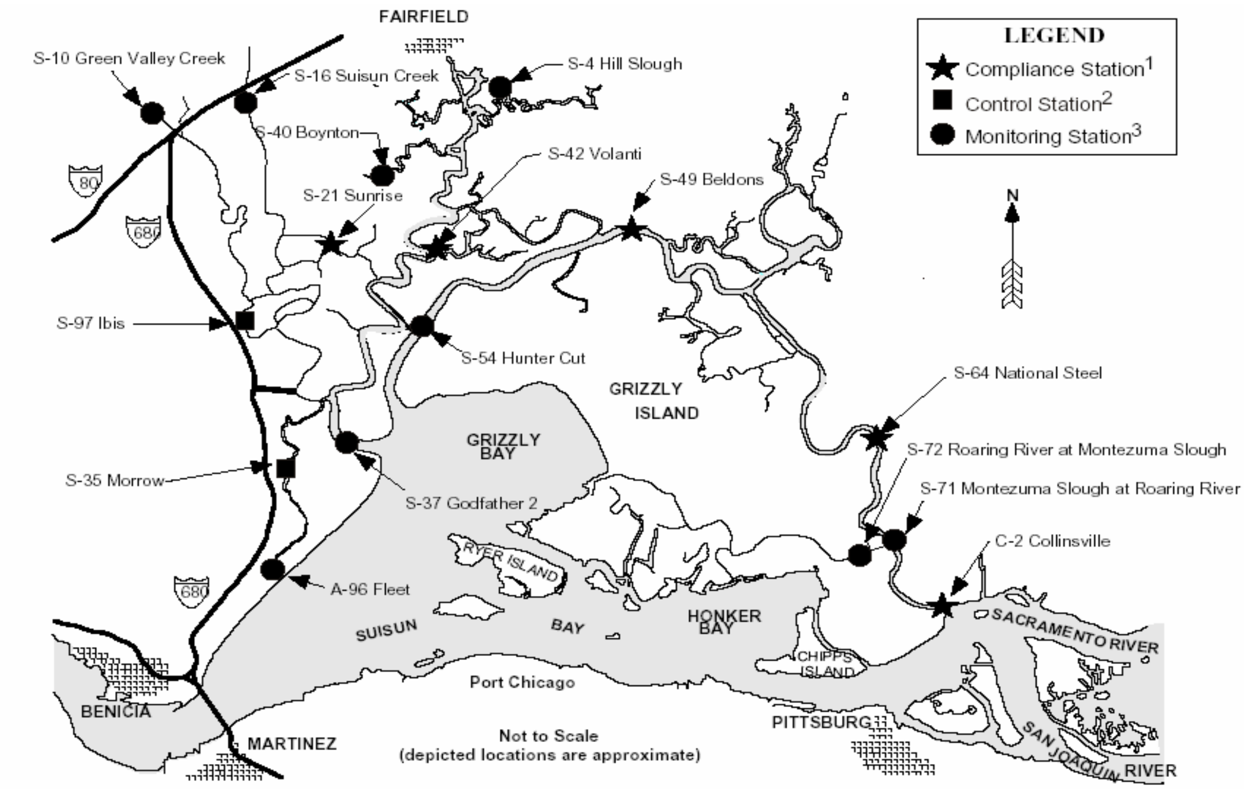


Figure 16. Water quality monitoring, control, and compliance stations located in Suisun Marsh. (Source: V. Pacheco.)

During the 1979-1980, DWR and the USBR constructed three major facilities (known as the "Initial Facilities," Figure 17) - the Roaring River Distribution System, the Goodyear Slough Outfall, and the Morrow Island Distribution System - to provide more effective water distribution to the clubs and public lands. Some important features of these facilities are:

- Roaring River Distribution System
  - – Takes water from east end of Montezuma Slough
  - – Provides water for approximately 5,000 acres on Simmons, Wheeler, Van Sickle and Hammond islands
  - – The eight, 48-inch culverts are screened by a common flat plate, profile wire, fish protective system. The screens were designed and constructed before winter Chinook and delta smelt screen criteria were refined and were designed to have an average screen face approach velocity of 0.5 fps at maximum flow. In reality the maximum flow is seldom achieved and thus approach velocities are almost always in the acceptable range for juvenile Chinook salmon and delta smelt.
- Goodyear Slough Outfall - this structure was designed to increase circulation and reduce salinity in Goodyear Slough by draining water from the lower end of Suisun Bay into Suisun Bay. This facility was designed to work in conjunction with the Morrow Island Distribution System.
- Morrow Island Distribution System

– The system is unscreened thus its operation is seasonally constrained by Chinook salmon and delta smelt take concerns.

– The system provides water to managed wetlands on Morrow Island that previously took water from Suisun Slough and/or Suisun Bay and helps channel drainage water to Grizzly Bay that previously entered Goodyear Slough. The Goodyear Slough Outfall was designed to work in conjunction with this facility to improve water quality in Goodyear Slough and subsequently water applied to the managed wetlands.

The Suisun Marsh Salinity Control Gates (SMSCG) on the eastern end of Montezuma Slough (just upstream of the Roaring River Distribution System, Figure 18) have been operating since 1988. The primary purpose of the SMSCG is to provide uni-directional flow through Montezuma Slough to limit salinity intruding into the marsh. The gates are operated tidally (open during ebb and closed during flood) during the October through May control period to meet SWRCB standards. To protect fish, the gates are not operated when monitoring data indicate that the standards would be met without their operation.

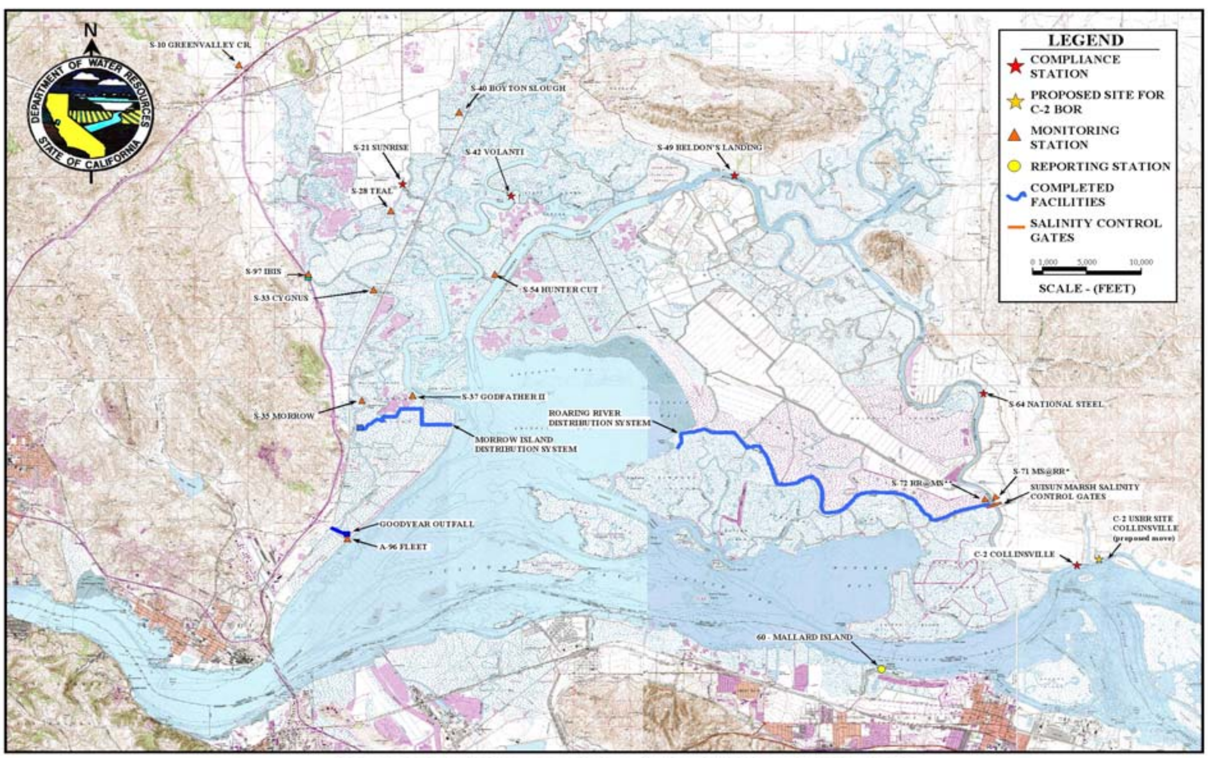


Figure 17. Suisun Marsh Program water quality monitoring and control infrastructure, including initial facilities. (Source: V. Pacheco.)

Figure 18. Suisun Marsh Salinity Control Gates. (Source: V. Pacheco.)

As shown in Figure 18, the SMSCG complex consists of the radial gates, a boat lock to allow boat movement in and out of Montezuma Slough, and flashboards to block the remainder of the channel During the non-control (summer) season, the flashboards are pulled to allow free passage of water, boats, and fish in and out of Montezuma Slough. Since the gates began operating in 1988, their basic operational mode has changed rather dramatically. Before they were constructed, the general belief was that the gates would be operated for the entire control season, except during the wet years. This operational mode was in place for five of the six initial years - the exception being 1993, a wet year. The 1993 winter Chinook biological opinion and the 1994 Delta Accord changed the operations to more of an “as needed” basis. Although the facility has been operated nine out of the past ten years, the gates have operated for the full season only three out of those ten years. Of the remaining years, January was the latest month in which the gates were operated - i.e. the flashboard remained in place. The gates were operated during the early fall months of those years to provide better water quality for initial fall flooding of ponds on private duck clubs and public wetlands.

One of the conditions in the USACE permit for construction of the control gate structure was a monitoring program to determine if the structure was causing a significant degradation or excessive predation on the aquatic system and implement any necessary mitigation in consultation with the fishery agencies, including removal of portions of the facility. The following brief description of fish passage studies at the SMSCG has been taken from IEP study reports and was not covered in detail by Pacheco. Studies at the salinity control gates have focused on the effects of the entire structure (flashboards, boat lock, and the gates themselves) and its operation on passage of adult Chinook salmon through Montezuma Slough. Adult salmon do not always remain in the mainstem rivers and may move into, and out of, sloughs and side channels on their way to upstream spawning grounds. Such side trips are part of the normal migratory process and do not cause problems as long as the fish arrive on the spawning, or holding grounds in case of winter and spring Chinook, without loss, or serious deterioration, of reproductive material or condition. The IEP has conducted three sets of studies on the effects of the gates on adult salmon migration in Montezuma Slough - 1993-1994, 1998-1999, and 2001-2003. Some preliminary results of the studies thus far are (R.Vincik, DFG, personal communication):

- The salinity control gates affect adult salmon migration.
- Salmon exhibit milling behavior in Montezuma Slough - i.e. they may enter the slough from the west, go up the slough some distance, and then exit from the west on their way to the spawning grounds.
- There are modifications to the facilities that can improve fish passage without compromising the ability to improve water quality downstream of the gates.
- There is an increase in salmon passage with the boat lock open.

There are no data to determine if gate operations are adversely affecting gamete quality and general body condition of salmon using Montezuma Slough as a migratory corridor.

Pacheco emphasized that Suisun Marsh levees are integral components of the Suisun Marsh water management infrastructure. In the marsh there are:

- about 123 miles of Class I levees that are subjected to high winds and wave action on islands, open bays and major sloughs. (These and the data below are from a 1983 report to the USACE.)
- about 72 miles of Class II levees subjected to medium wind action and are mostly on secondary sloughs.
- about 34 miles of Class III levees subjected to low wind action in the small inner sloughs.

Many of the levees were originally constructed over 150 years ago and now range in height from 4 to 8 feet. Levee maintenance problems involve soil consolidation, erosion by waves and tidal currents, overtopping, and seepage. Landowners maintain the external levees, subject to strict provisions of USACE Regional General Maintenance Permit. No maintenance activity is permitted that may adversely affect listed species or their critical habitat. Meeting this criterion requires that SRCD work with the resource agencies in obtaining necessary permits for levee work in Suisun Marsh.

The CALFED Levee Investigation Team (1999-2001) concluded that ongoing subsidence in Suisun Marsh requires an active levee maintenance program to avoid large scale flooding and conversion to vast open water areas. Increasing hydrostatic pressure can result from continuing subsidence on managed wetlands combined with projected sea level rise. Although tidal restoration can provide a beneficial effect by reducing tidal heights, funding for both maintenance and improvements of levees are necessary to protect water quality in both Suisun Marsh and the Delta.

Suisun Marsh Vegetation

One of the primary goals of Suisun Marsh wetlands managers is to provide waterfowl habitat and hunting opportunities. Next to the water itself, vegetation is the most important habitat component, with the vegetation providing food, shelter from the elements and predators. Wetland managers use burning, disking, mowing, and duration of flooding to help establish and maintain the plant communities that provide the most productive waterfowl habitat. The individual plant species have specific tolerance levels for the duration and depth of flooding, the salinity of the applied water and the salinity in the soil profile. The composition and density of the vegetation is also important to such at-risk non-waterfowl species as the salt marsh harvest mouse and clapper rails.

The vegetative community in Suisun Marsh can change in response to active management actions (such as flooding and draining cycles), introduced species (such as perennial pepperweed), failure to pursue active management (cattail and tule dominance in ponds that are not burned, disked, or with poor water management). The native vegetation of Suisun Marsh consisted of tules (*Scirpus* sp.), cattails (*Typhus* sp.), and rushes (*Juncus* sp.) in those areas of continuous flooding. Salt grass (*Distichlis spicata*) usually dominated on higher ground infrequently flooded, with pickleweed occurring in areas of poor drainage. Although the methods may not have been as quantitative as desired, the information in Table 4 (adapted from George et al. 1965) provides an idea of the broad overall vegetation composition in 1960.

Table 4. Results of the 1960 Suisun Marsh Vegetation Survey (From George et al. 1965)

Vegetation Type	*Acreage*	*Percent of Cover*
Pickleweed	13,546	25
Salt grass	12,928	24
Annuals	5,862	11
Crops	4,379	8
Alkali bulrush	3,333	6
Tule	2,929	5
Cattail	2,476	5
Baltic rush	1,827	3
Brass buttons	1,128	2
Olneyi bulrush	521	1
Bare ground	262	1
Miscellaneous	5,307	9

It is interesting to note that the target waterfowl plant species, alkali bulrush and brass buttons occupied only an estimated 11 percent of the total vegetative cover in the early 1960s.

To keep track of changes in marsh vegetation, the 1999 Suisun Marsh monitoring agreement requires that DWR and the USBR fund the vegetation surveys listed below. (The field truth required for the surveys also helps follow the distribution and abundance of rare and listed plant species.)

- Vegetation occurrence on lands within 35 meters of all soil water monitoring sites conducted annually during August or September.
- Seed production of alkali bulrush and fathen located within 35 meters of each soil water monitoring site estimated annually each year.
- Overall vegetative composition of the Suisun Marsh conducted every third year. The aerial photographs used for the triennial vegetation survey will also be used to estimate net acreage changes in preferred salt marsh harvest mouse habitat.

DFG conducts the vegetation surveys to determine vegetation trends and, if possible, to relate those trends to management practices and quality of the water used to flood the ponds. Todd Keeler-Wolf (DFG) presented information at the workshop about the triennial surveys, which forms the basis of the remaining discussion.

Keeler-Wolf first presented the results of the 1999 vegetative survey (Figure 19) to demonstrate the wide variety of vegetative types and the complexity of the resulting vegetation map. Each polygon in the map has the following attributes:

- Vegetation association/mapping unit
- WHR habitat type
- Holland vegetation type
- Height class
- Density class
- Disturbance category
- Disturbance intensity

Figure 19. Vegetation of Suisun Marsh as of June 1999. (Source: T. Keeler-Wolf.)

The following change detection process is used to compare the vegetative data in 1999 to that found in subsequent surveys, such as the 2003 survey.

- Adjust 1999 line work to match 2003 aerial photography (rubbersheeting)
- Print 1999 line work on mylar sheets, including polygon number and vegetation type
- Overlay mylar on 2003 aerial diapositives using a light table and magnification
- Identify and record change as defined in protocol
- Input change data into project GIS and database
- Between the 1999 and 2000 surveys, the protocols detected the following changes in the marsh:
  - Change detected on 515 acres (0.74% of study area)
  - Intertidal wetlands accounted for 12 of these acres
  - 65 acres of *Salicornia virginica* were lost; 70% of which was converted to *Scirpus maritimus*
  - *Lepidium latifolium* (perennial pepperweed) increased by 18 acres exclusively in managed wetlands
  - *Phragmites australis* (common reed) increased by 20 acres
  - Construction was greatest apparent cause for change
  - Surveys also showed that there was no change between the two years in salt marsh harvest mouse habitat in the Benicia SMHM habitat unit.

The 2003 survey was designed to overcome some of the shortcomings noted in previous surveys and used greater resolution aerial photography. The 2000 change detection analysis indicated relative stability - thus supporting the idea that a 3-year cycle was adequate to detect changes in the marsh vegetative community. However, recent completion (following this presentation in March 2004) of the second change detection conducted using summer 2003 aerial photography shows a more significant change over the 4 year period between 1999 and 2003. From 1999 to 2003, there were changes to 5158 vegetation polygons representing 10,935 acres. Thus, 15.8% of the study area was interpreted to have changed in those 4 years.

These changes were not evenly distributed over the 133 vegetation types. Medium Wetland Graminoids, *Scirpus maritimus*, Short Wetland Herbs, Medium Wetland Herbs and *S. maritimus*/*Salicornia virginica* were the five types with the greatest increase in acreage. *Distichlis spicata*, *Salicornia*, *Distichlis*/Annual Grasses, *Distichlis*/*Salicornia*, and Flooded Managed Wetlands were the five types with the greatest decrease in acreage over the study period. Urban areas increased by 103 acres, primarily due to construction in Benicia and Cordelia. Construction of new levees in the eastern portion of the marsh and on Joice Island contributed to 54 acres of new roads/levees and 44 acres of new ditches. There was an overall 682 acre decrease in all *Salicornia virginica* types from 1999 to 2003.

Several non-native species of concern increased in cover over the study period. Eight non-native species represented by 17 vegetation types or map units increased by a total of 537 acres. These species were: *Arundo donax*, *Carpobrotus edulis*, *Centaurea solstitialis*, *Conium maculatum*, *Eucalyptus* species, *Foeniculum vulgare*, *Lepidium latifolium*, and *Phragmites australis*.

In the event that field observations indicate significant changes within one year, the aerial surveys may be instituted to capture these changes. For example, additional surveys could be called for if it appears that perennial pepperweed (*Lepidium latifolium*) or other exotic plants appear to expanding their territory, or if management techniques appear to be diminishing certain critical vegetation. The results and lessons from current effort may lead to further refinements and recommendations. Further results of the most recent change detection are available through the ECAT group (contact Terri Gaines or Cassandra Enos of DWR, Division of Environmental Services).

Birds

Waterfowl

The workshop focused on three avian groups that use the marsh, namely waterfowl, rails and tidal marsh birds. There were two presentations on Suisun Marsh waterfowl, one by Mark Petrie (Ducks Unlimited) on the current role of Suisun Marsh in the Pacific Flyway and waterfowl food habits. The second was by Josh Ackerman (UCD) on wintering and breeding waterfowl in Suisun Marsh. I discuss waterfowl in that order - i.e. from the flyway to the marsh in particular.

There are about 100 million birds using the Pacific Flyway. In California, there are specific populations objectives for the Central Valley and for Suisun Marsh (Figure 20, plates a and b). As shown another way in Figure 21, Suisun Marsh provides about 5 percent of waterfowl distribution in the Valley. Although this seems to be relatively small percentage, the marsh provides important habitat for several waterfowl species.

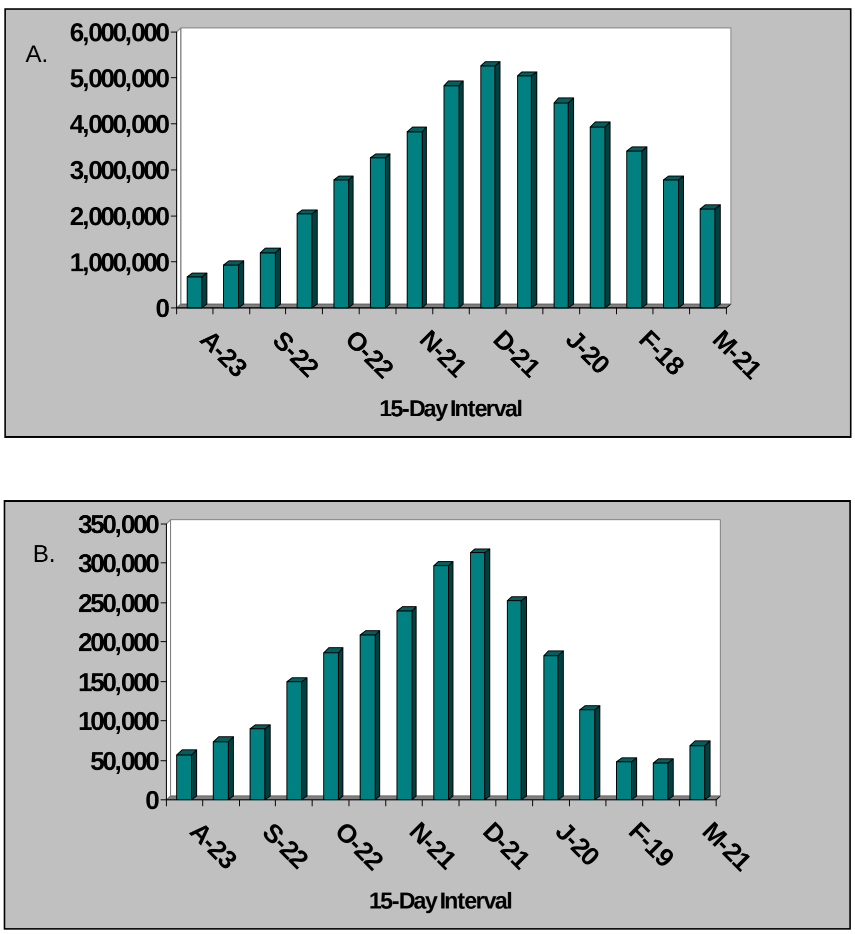


Figure 20. Central Valley and Suisun Marsh waterfowl population objectives by month, plates A and B. (Source: M. Petrie.)

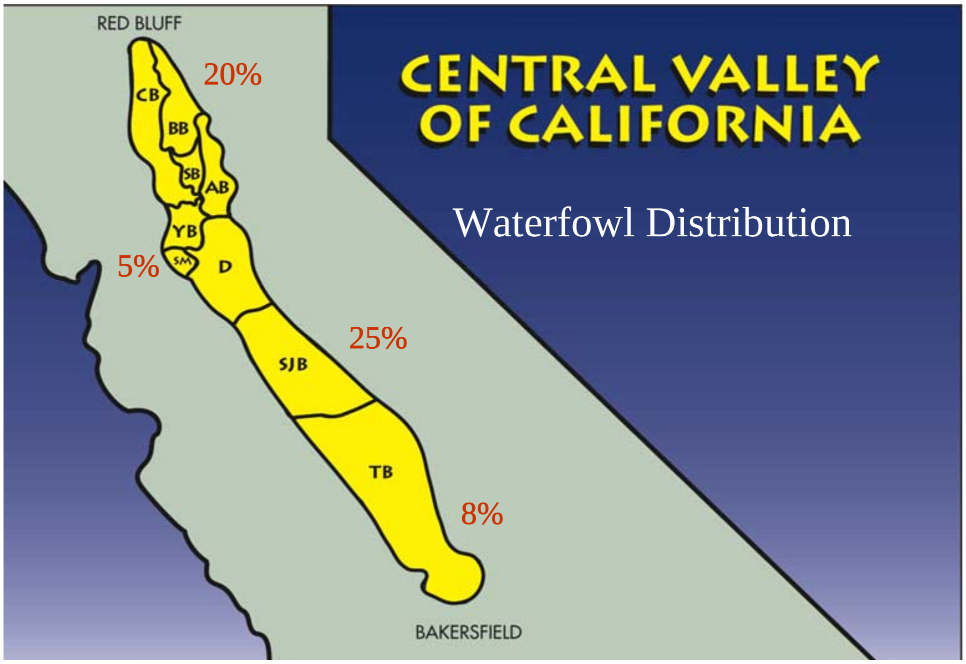


Figure 21. Waterfowl distribution in California's Central Valley, including Suisun Marsh. (Source: M. Petrie.)

Petrie also described a stochastic habitat model for wintering and migratory waterfowl - a model which energetically based and is scale and region independent. The model can be used to estimate the effects of changes in land use or management practices on waterfowl habitat value. For example knowledge of the birds' food habits (Figure 22), energy needs and the amount of food in the area can be used to compare energy supply and demand. This tool can be used to assess the effects of management actions, e.g. tidal wetland restoration, on habitat carrying capacity. The model is presently of limited use in the marsh because we do not have adequate data on food densities in the tidal and non-tidal wetlands.

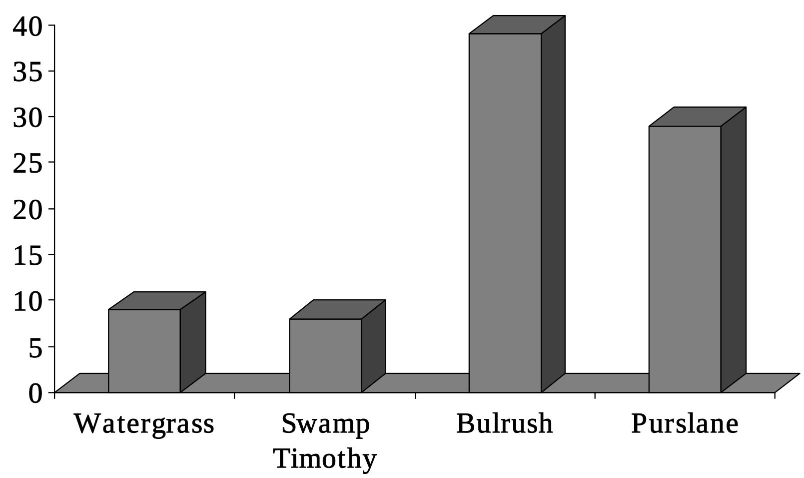
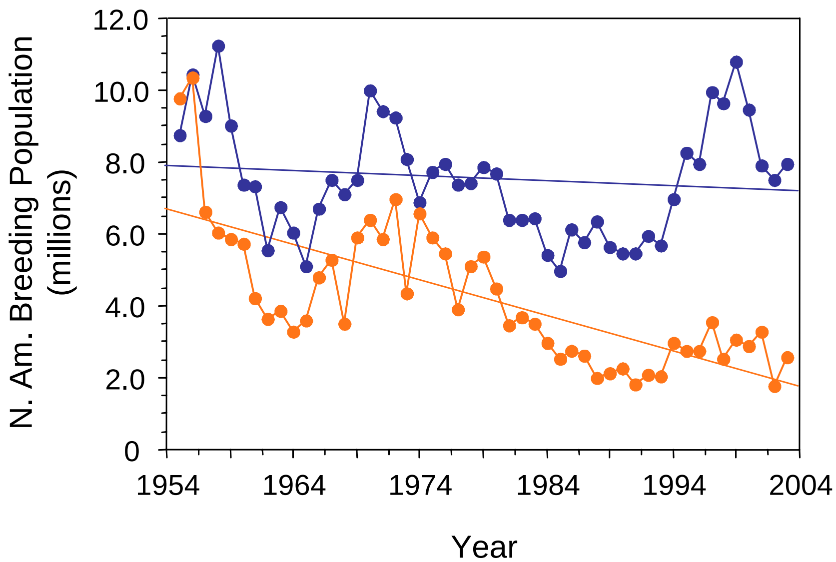


Figure 22. Pintail diets in Suisun Marsh. (Source: M. Petrie.)

Ackerman emphasized that the Suisun Marsh is an important area for both wintering (visiting) and breeding waterfowl populations. In the past much of the hunting was centered on pintail due to their relative abundance. As shown in Figure 23, pintail populations have recently exhibited severe declines in both North America (bottom graph) and in the Suisun Marsh (top graph). On the other hand, mallard populations have mostly held their own. Most of the mallards harvested in California originate in California (Figure 24) and the Suisun Marsh is a major California breeding area. In Suisun Marsh, mallards are by far the dominant waterfowl in the upland nesting areas. In Suisun Marsh, mallards are the most common breeding waterfowl in the upland nesting areas. Mallard nesting success has declined over the last two decades (Figure 25), and is highly dependant on alternate prey resources of predators. The diets of three marsh waterfowl (Figure 26) are varied and somewhat species dependent.



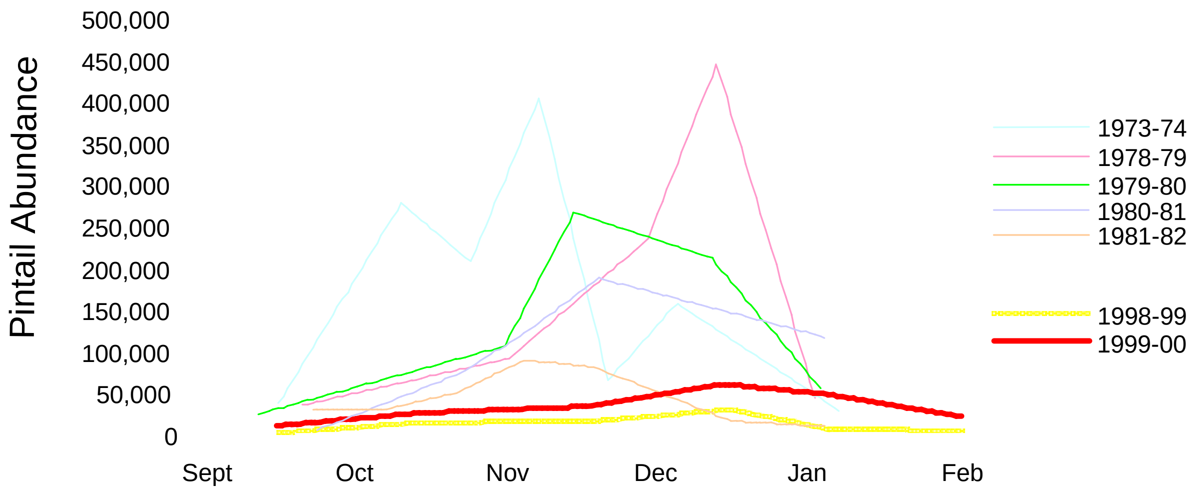


Figure 23. Trends in pintail abundance in North America (top) and Suisun Marsh (bottom). (Source: J. Ackerman.)

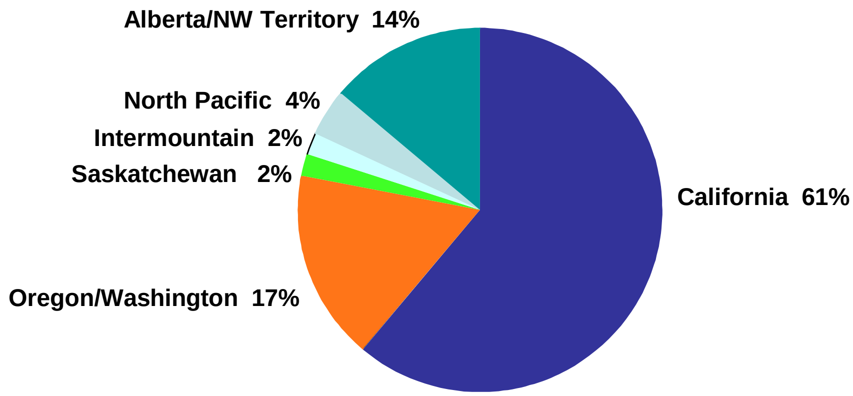


Figure 24. Breeding ground origin of mallards harvested in California. Source: Pre-season CWA banding from 1990-1994, ages and sexes combined. (Source: J. Ackerman.)

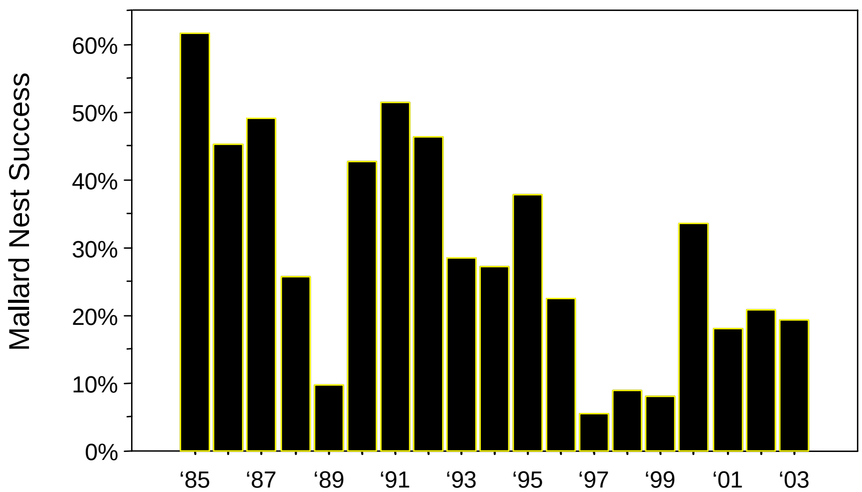


Figure 25. Mallard nest success in Suisun Marsh, 1985–2003. (Source: J. Ackerman.)

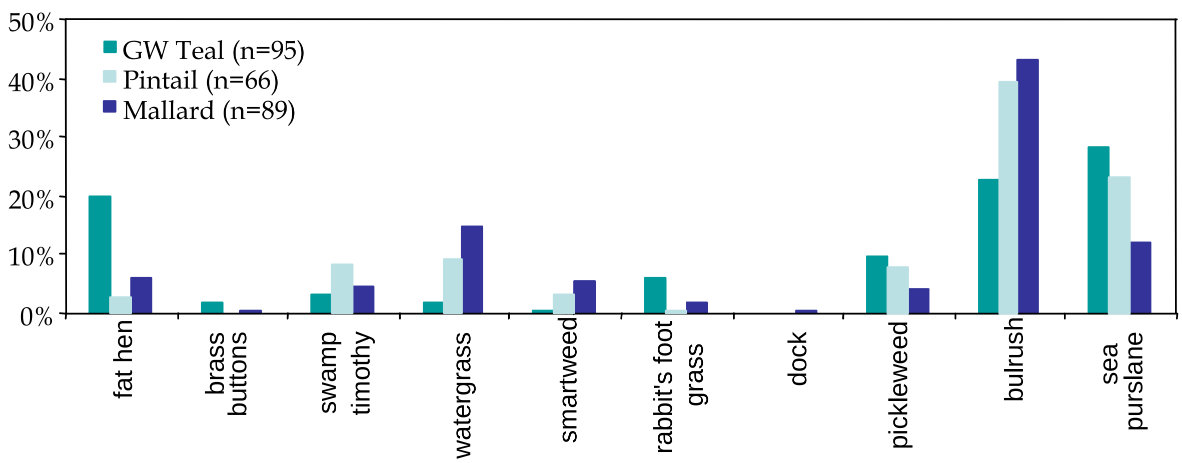


Figure 26. Diet of ducks collected in Suisun Marsh in 1998. (Source: J. Ackerman.)

Dabbling ducks use shallow water habitat, typical of duck hunting clubs, whereas diving ducks use the deeper water bays and sloughs of Suisun Marsh.

Ackerman summarized our knowledge of wintering and breeding waterfowl in Suisun Marsh as follows:

Wintering Waterfowl

- Waterfowl management focus in the marsh has changed from pintails to mallards
- Ducks feed on duck clubs (managed marshes) at night
- Duck clubs provide essential habitat diversity and food

Breeding Waterfowl

- Suisun Marsh duck production is important for Pacific Flyway
- High nest success and breeding densities are found in Suisun Marsh
- Nest success depends on environment, including nest density and availability of alternate prey.

Ackerman also stressed two areas where we need more knowledge, namely:

1. Effects of restoring habitat to tidal marsh on breeding and production.
2. The effects of salinity on duckling habitat use and survival.

Rails

This discussion is based on the workshop presentation by Jules Evens of Avocet Research. There are several members of the family Rallidae found in Suisun Marsh, namely:

- yellow rail
- California black rail
- California clapper rail
- Virginia rail
- Sora
- American coot
- Common moorhen

The Virginia rail is a species of special concern, the clapper rail is state and federal listed as endangered, and the black rail is California listed as threatened. The other species have no special status. I restrict this discussion to the black (*Laterallus jamaicensis coturniculus*) and clapper (*Rallus longirostris obsoletus*) rails. (California clapper rail shown below).

The black rail is secretive denizen of the high marsh plain and the Suisun Marsh may hold half of the Estuary's extant population. Relatively high elevation and cover are important factors in black rail population success. Black rail habitat requirements include:

- 100% vegetative cover
- Moist, undisturbed substrate
- Freshwater influence
- Area
- Quality of peripheral vegetation
- A terrestrial insects and amphipod prey base

Table 5 shows estimated black rail habitat abundance by region in the estuary. Rail abundance is affected by habitat quality, which in turn is affected by: the presence of relatively undisturbed, or mature, old marsh with unrestricted tidal influence; limited predator population and/or well-developed refugia, and; relative freedom from the effects of urbanization, hardened edges, rising sea level, stochastic events, inadvertent hydrological changes, etc. - i.e. habitat that is in short supply in the San Francisco Estuary.

Table 5. Black rail habitat and abundance by region.

Location	*Size (total ha of habitat)*	*Mean Abundance Index +/- S.E.*	*Mean Abundance Index*	*No. of Sites*	*Abundance Estimate Based on Median*	*Adjusted Abundance Estimate from Distance*
San Pablo Bay	5531	1.25 +/-0.345	0.71	13	3,930	7,100
Suisun & Carquinez	3780	1.43 +/- 0.320	1.08	5	4,080	7,200
Outer Coast	543	0.46 +/- 0.196	0.30	5	163	289

The clapper rail is a rare "year-round" resident (?) residing in larger marsh parcels adjacent to tidal channels with the following characteristics:

- Fully tidal marshes

- Channels nearby
- Range in elevation
- Older and larger marshes
- Contiguity with other marshes providing similar habitat
- Refugia present
- *Spartina* or *Scirpus* dominate the vegetative cover

The present clapper rail density around the estuary is approximately:

- South Bay 0.23/ha (range 0.17-0.26)
- San Pablo 0.27/ha (range 0.17-0.91)
- Suisun Bay 0.15/ha (range 0.01-0.33)

There is some research on clapper rails, e.g.

- Suisun population study (CDFG) 2002-04
- Baywide population 2004-06 (CALFED, etc.)
- Invasive Spartina Project
- Discrete project impacts
- Infrastructure impacts (e.g. Cordelia Slough)
- Restoration monitoring (e.g. Integrated Regional Wetland Monitoring Program by Siegel et al. 2002)

More research and management are needed to monitor and recover clapper rails in the estuary including: annual surveys. restoration design, demographic information, predator control, habitat enhancement, habitat corridors, and protection and identification of source problems.

Evens left the group with the following take home messages.

- The bulk of the extant populations of the black and clapper rails exist within the San Francisco Estuary system.
- Each species is a key component of a healthy and functional tidal marshland
- Each species is highly sensitive to environmental variables-changing salinity values, water levels, predation pressure, and human impacts.
- The presence or absence of these species provides a critical indicator of marsh viability.
- Enhancement of rail habitat benefits other marsh-dependent species!

Tidal Marsh Birds of Suisun Marsh

Nadav Nur's (Point Reyes Bird Observatory, PRBO) description of the population status, habitat associations, and patterns of reproductive success of three song sparrow sub-species, the yellow throat and the

California black rail provide the basis for this discussion. This discussion is focused on the song sparrow, *Melospiza melodia*, with particular emphasis on the Suisun song sparrow, *M. m. maxilaris*. All three subspecies - Alameda, Samuel's and Suisun - are species of special concern.

As background, Nur emphasized that tidal marsh was once the predominant habitat in San Francisco Estuary. Approximately 80% of this habitat has been lost over the past 150 years by conversion to agriculture, to commercial salt ponds, and assorted development). The remaining tidal marsh habitat has been altered from the original by:

- habitat fragmentation,
- man-made structures,
- levees, dikes, channelization,
- changes in salinity
- invasive species, contaminants, and other threats

In spite of the extensive habitat losses and changes many endemic species or subspecies of bird have evolved specifically to use tidal marsh habitat. In 1996 the observation that endemic avian species continued to use tidal marsh habitat provided the impetus for PRBO's Tidal Marsh Project. The Tidal Marsh Project now encompasses 60 study marshes, 500 survey locations, and eight years of intensive study. The study objectives are:

1. Determine population status, trend of each species or subspecies.
2. Identify important habitat features and vegetation characteristics that birds respond to, or require

   – local scale (a bird's territory or home range)

   – broader, regional scale

That is, evaluate importance of landscape: adjacent land use, habitat fragmentation.

3. Understand population processes supporting viable populations:

   – Focus on: Level of reproductive success, and how variable is it.

   – Information on other demographic parameters.

   – Adult survival, Juvenile survival, Dispersal

– Synthesize into a population dynamic model to determine viability

4. Assess tidal marsh habitat and guide restoration using birds as indicators

   – What characterizes “healthy” functioning marsh habitat, from the perspective of birds?

   – What are important habitat features and landscape characteristics?

   – How can this information be used to guide present and future Tidal Marsh restoration?

   – What should we be monitoring to evaluate success?

   – How does bird use of a marsh change over time in a successful marsh restoration?

As shown in Figure 27, the Suisun Song sparrow is found throughout the Suisun Bay, Suisun Marsh area, with higher densities found along the Bay shorelines. The total song sparrow population in the estuary has apparently been rather stable (Table 6), but s 35% decline in the Suisun song sparrow is cause for concern.

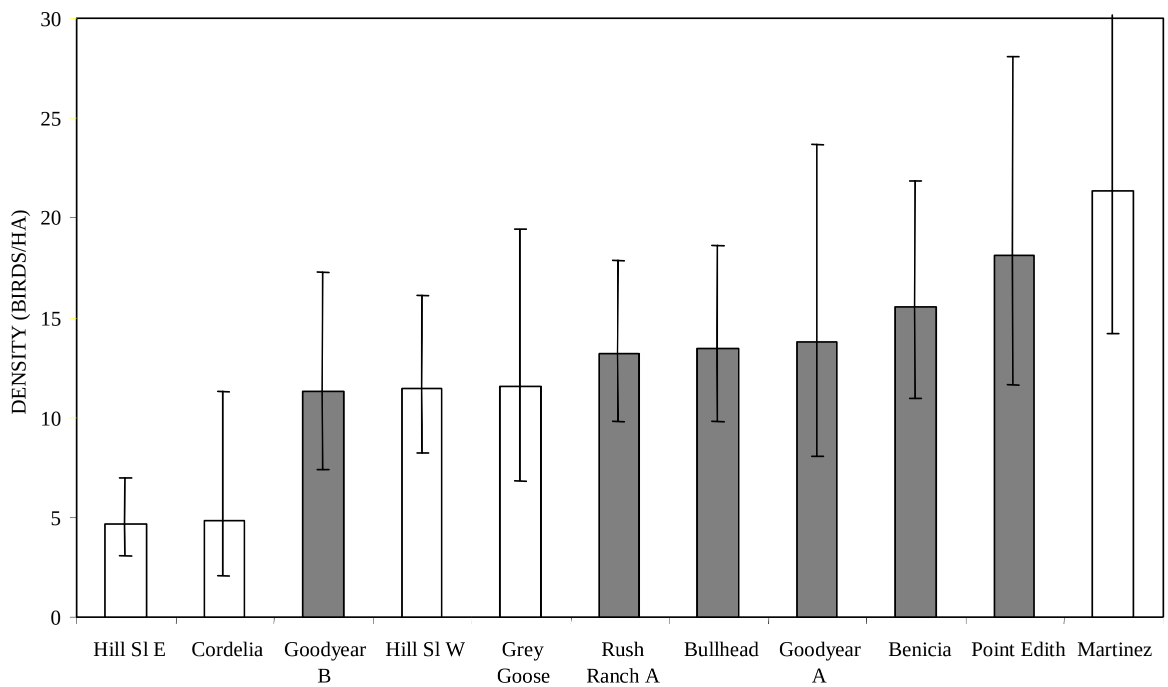


Figure 27. Suisun Song sparrow mean density in Suisun Bay, March-April 2000. (Source: N. Nur.)

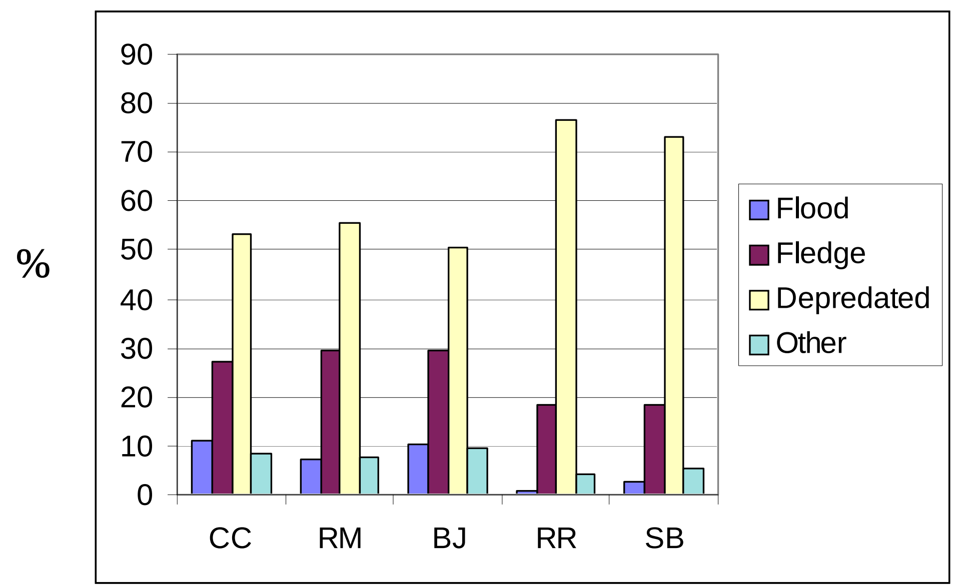
Table 6. Estimates of Suisun song sparrow population size in San Francisco Estuary

Region	*Marshall and Dedrick (1990 and earlier)*	*PRBO Estimate 1996*	*PRBO Estimate 2000*
San Francisco Bay	14,800	9,650	15,200
San Pablo Bay	31,200	83,400	77,400
Suisun Bay	19,100	68,000	44,500

Predictive modeling song sparrow’s and yellow throat’s probability of occurrence indicates that:

1. All species respond to local habitat features, at a fine scale.
2. Local habitat variables can account for much of the variation in abundance or occurrence
3. Species respond to both general habitat features and species-specific vegetation
4. Landscape factors account for high proportion of variation in abundance/occurrence as well.
5. Birds are not likely responding to landscape factors directly, so causal factors remain to be elucidated.
6. Landscape models alone can provide reasonable predictive models, but are improved greatly by inclusion of local habitat features
7. In some cases different species responded to the same factor (e.g., Bulrush, Coyote Brush), but in other cases species responded differently.
8. Thus no one species can be a good proxy for the other 3 species - multi-species management is needed.

PRBO investigated song sparrow reproductive success at five sites - three in San Pablo Bay and two in Suisun Marsh at Rush Ranch. Between 1996 and 2003, researchers examined around 2,600 nests. As shown in Figure 28, nesting success was not very good at all sites, including those at Rush Ranch, with the most likely cause being depredation. The data are plotted on an annual basis in Figure 29. Probability of nesting success is low overall, but particularly low in Suisun Marsh - being on the order of 10-15 percent. The population model shows that a nesting success of around 30 percent is needed to maintain population stability. Nur presented data showing that nesting success was negatively correlated with the distance the nest was from water's edge, with Rush Ranch sites being the most distant - and having the lowest success.



Site Codes: RM = Petaluma River Mouth BJ = Black John Slough SB = Benicia CC = China Camp RR = Rush Ranch

Figure 28. Outcome of song sparrow nesting attempts in San Francisco Bay. Site codes: RM - Petaluma River mouth; BJ - Black John Slough; SB - Benicia; CC - China Camp; RR - Rush Ranch. (Source: N. Nur.)

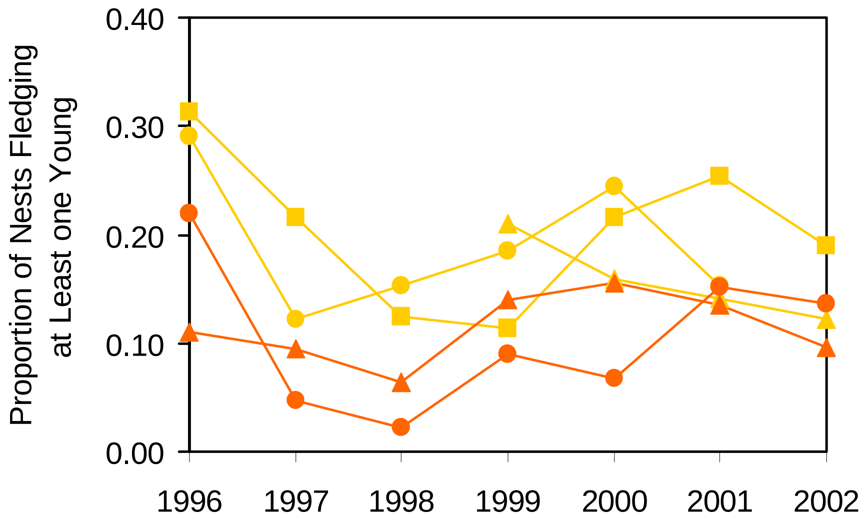


Figure 29.Variation is song sparrow survival among sites and among years. (Source: N. Nur.)

Nur's overall conclusions were:

- There is evidence for decline in population size of Suisun song sparrows
- Status of salt marsh common yellowthroat is not known; studies of this species are called for
- Predation on nests is of great concern.
- Predators may be native or non-native.
- Due to low nesting success, population viability is in question.
- Since each species responds differently to the set of local habitat and landscape variables; multi-species management is needed.
- Vegetation complexity and diversity is most favorable to tidal marsh species.
- Heterogeneity of marsh habitat is also important: channels are important for tidal marsh birds, and ponds and channels in marshes provide habitat required for waterbirds.
- PRBO researchers are now exploring whether young, restored marshes can provide the vegetation complexity and diversity needed to support native tidal marsh bird populations.

Mammals

Although there are about 47 mammalian species in Suisun Marsh, I only include the two species presented at the March 2004 workshop are included in this summary, namely, the salt marsh harvest mouse and the river otter.

Salt marsh harvest mouse, <u>Reithrodontomys raviventris halioetes</u>. Diego Sustraita's (CSU Northridge and DFG) workshop description of the salt marsh harvest mouse (SMHM) in Suisun Marsh provided the basis for this discussion. Sustraita began by listing the large numbers of mammals found in Suisun Marsh including about 16 species of native bats, 22 other native species (Table 7) and 9 introduced species including the opossum, house mouse, Norway rat, feral cats, American beaver and feral pigs. In his presentation, Sustraita used the SMHM as a case study but emphasized the need to include consideration of the entire mammalian community in marsh planning.

Table 7. List of mammals found in Suisun Marsh. (Adapted from data presented by Diego Sustraita at the 2004 Suisun Marsh workshop.)

Native Bat Species (16)	*Other Native Species (20)*	*Introduced Species (9)*
Little brown *myotis*	Ornate shrew	Virginia opossum
Yuma *myotis*	Suisun shrew[a, b]	House mouse
Long-eared *myotis*	Broad-handed mole	Norway rat
Fringed *myotis*	California vole	Black rat
Hairy-winged *myotis*	Gray fox	Feral cats
Small-footed *myotis*	Western harvest mouse	American beaver[c]
California *myotis*	Coyote	Muskrat[d]
Hoary bat	Botta’s pocket gopher	Feral pig[e]
Pallid bat[a]	Raccoon	Red fox[f]
Townsend’s big eared bat[a]	Beechey ground squirrel	
Brazilian free-tailed bat	Bobcat	
Western mastiff bat (SSC)	Tule elk	
Silvery-haired bat	Black-tailed jack rabbit	
Big brown bat	Striped skunk	
Western pipistrelle	Spotted skunk	
Red bat	American badger	
	Long-tailed weasel	
	American mink	
	Deer mouse	
	River otter	

a. Species of special concern.
b. Sparse occurrence.
c. Population escalating.
d. Cause significant impact to levees.
e. On-going hunting minimally successful.
f. Presumed not to occur in the marsh.

Earlier studies (e.g. Fisler 1965, Bias 1994, Shellhamer et al. 1988 and Padgett-Flohr and Isackson 2003) had shown that:

- Pickleweed provided the primary salt marsh harvest mouse habitat.
- Habitat quality increased with depth, density and degree of intermixing with other halophytic species.
- SMHM presence was associated with mid-range salinity levels

Brown (2003) used DNA analyses to show that there are two clades of SMHM in Suisun Marsh and that *R. raviventris* is a sister taxon to *R. montanus*, not the western harvest mouse, *R. megalotis*. Although the western harvest mouse is found in Suisun Marsh, there appears little chance that the two species have, or will, hybridize.

DWR and DFG conducted a SMHM study to develop a better understanding of base-line SMHM biology and ecology in Suisun Marsh. The study used trapping at tidal and managed wetlands stations and microhabitat stations to examine seasonal demographic patterns and broad-scale micro and macrohabitat associations. The study results and management implications can be summarized as follows:

- There was a gradual increase in SMHM density over the limited duration of the study.
- Pickleweed and mixed halophytes seemed equally important as SMHM habitat.
- Diked wetlands appeared to support higher SMHM densities than tidal wetlands, however the mouse's reproductive potential and survival were similar in both habitat types.
- Demographic response seemed to be a reasonable proxy for habitat quality.

The investigators plan to continue the study for a second annual cycle and will include radiotelemetry in the next phase. To wrap up the study, Sustraita showed a conceptual model of how mammals use Suisun Marsh (Figure 30).

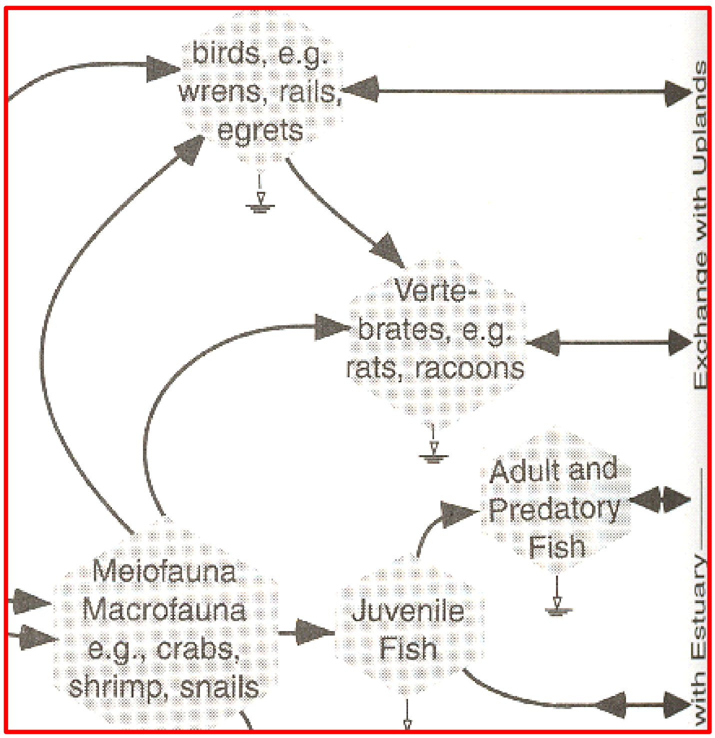


Figure 30. Suisun Marsh mammals and conceptual models. (Source: Diego.)

River otter, __Lontra canadensis__. As described at the workshop by Tasha Belfiore (UC Berkeley), the river otter is a perfect example of a "charismatic macro-fauna." The otter was historically widely distributed throughout California and North America. Although little work has been done on the species in most locations in California and elsewhere, rivers otters were harvested widely in California declined before trapping became illegal after the 1960-61 season.

Much of what is known about the biology of river otters comes from studies of riverine communities and studies done by individuals outside of California. Much less is known about otter life history characteristics in a marsh environment. For example, otters are efficient fish predators in rivers, but in marshes they may become more opportunistic feeders. In Suisun Marsh, dikes and flow control structures have changed the system dramatically and may be affecting the abundance and distribution of the river otter.

The numbers of river otters in Suisun Marsh are unknown but Belfiore postulated that the marsh may provide for dense populations because of relatively mild climate, abundant food, and lack of resource limitations do not cause the animals to become territorial. In limited diet studies conducted on the marsh population (Grenfell 1974; Belfiore unpublished data) crayfish remains were the most common food item found in scat. Although waterfowl were second, the amount of waterfowl remains in their fecal deposits seemed to be tied to waterfowl abundance and eggshells from coots, ducks and other waterfowl were never found. Fish remains were seldom found with the scat containing the remains of other invertebrates, mammals and reptiles. Plant remains were also found.

The otters move from swimming in large or small groups in open waters, to foraging or, denning, scent marking, mating, and sunning in the vast network of Suisun Marsh channels, pools, flats, and vegetated banks.

According to Belfiore, there is a lot to learn about river otters in Suisun Marsh including:

- How do they use the various habitats in the marsh?
- What is the impact of their opportunistic feeding strategy on waterfowl and other marsh invertebrates?
- Can the local environment be enhanced to increase the species' chance for continued existence?
- What are the impacts of contaminants (both in the water and the food supply) on river otters?
- What does the biology of otters in Suisun Marsh tell us about the biology of otters in other locations?

Biotic Communities of Marsh Channels

Channels are an integral part of a marsh landscape. The channels provide a home for numerous species of fish and their supporting foodweb. The channels also provide the corridor for water movement into and out of the marsh and the source of water applied to the marshes duck clubs. As mentioned earlier, channel water salinity is influenced by the tides, freshwater inflow (both local inflow and from the Sacramento and San Joaquin rivers), and local drainage practices. The main channels in the Suisun Marsh are Montezuma, Suisun, Peytonia, Cutoff, Boynton; Peytonia and Nurse sloughs are the largest.

This section describes the roles of Suisun Marsh sloughs in supporting the fish assemblages found in the marsh, as well as those plants and animals that make up their food base. Two water quality aspects of the channel waters - dissolved organic carbon and dissolved oxygen -- are also included. Endangered species act listings of several fish - including winter Chinook in 1989, delta smelt in 1993 and Sacramento splittail in 1994 - and subsequent actions to protect the listed fish have increased the need to understand the role of the marsh in affecting their distribution and abundance.

The Foodweb. Since the estuary is an area where fresh and salt waters mix and the location of the mixing zone can change on different time scales (from daily to seasonal to inter-annual) and the numbers and kinds of organisms making up the food base is quite variable and complex. Superimposed on this natural variability are such human induced effect such as the introduction of non-native invasive species and contaminants. The water column foodweb components range from microscopic bacteria and planktonic (free floating) algae and protozoa, barely macroscopic animals (zooplankton) to larger animals such as shrimp and larval fish. Many fish are also able to obtain a portion of their food supply from organisms dwelling on the channel bottoms - the benthos. Runoff from tidal marshes containing decomposing plant and animal material provides part of the nutrients and food resources needed to maintain the foodweb in the estuary. Figure 31 from a workshop presentation by Anke Mueller-Solger provides a conceptual overview of the foodweb in marsh channels. “Bog brew” and “swamp stew” consist of a complex mix of live and dead organisms at the bottom of the marsh food web that are part of the complex process by which fish, otters, water birds, etc. obtain all or part of their food supply.

Figure 31. The complex Suisun Marsh food web. (Source: A. Mueller-Solger.)

There are four components of the food web in marsh channels - the phytoplankton, the zooplankton, the larger invertebrates and the benthos. The general goal is to determine if there are trends in the abundance of organisms in the different communities and if the food web base itself might be limiting to marsh fish assemblages. If there are trends, then the general question becomes, what caused them? The material is adapted from presentations by Anke Mueller-Solger (phytoplankton and zooplankton) and Robert Schroeter (larger invertebrates and benthos).

Phytoplankton. Phytoplankton can be considered the grass of the open water in that these microscopic plants convert sunlight energy and inorganic carbon to organic carbon. Too little phytoplankton biomass can limit fish production and too much can cause dissolved oxygen sags and other problems (eutrophication). Phytoplankton growth rates and biomass accumulation are a complex function of water clarity, nutrients, particle residence time, predation and contaminants.

Phytoplankton biomass, as indicated by spring concentrations of chlorophyll *a* (an algal pigment) at two Suisun Marsh channel stations has declined dramatically during since 1975 (Figure 32, upper panel). The chlorophyll *a* decline observed in the marsh is consistent with that found in stations outside the marsh (see bottom panel of Figure 32). The reasons for the decline in both areas are unknown may in part due to an introduced clam (*Potamocorbula amurensis*) (Kimmerer and Orsi 1995), changed hydrological conditions, or climatic factors (Lehman 2004).

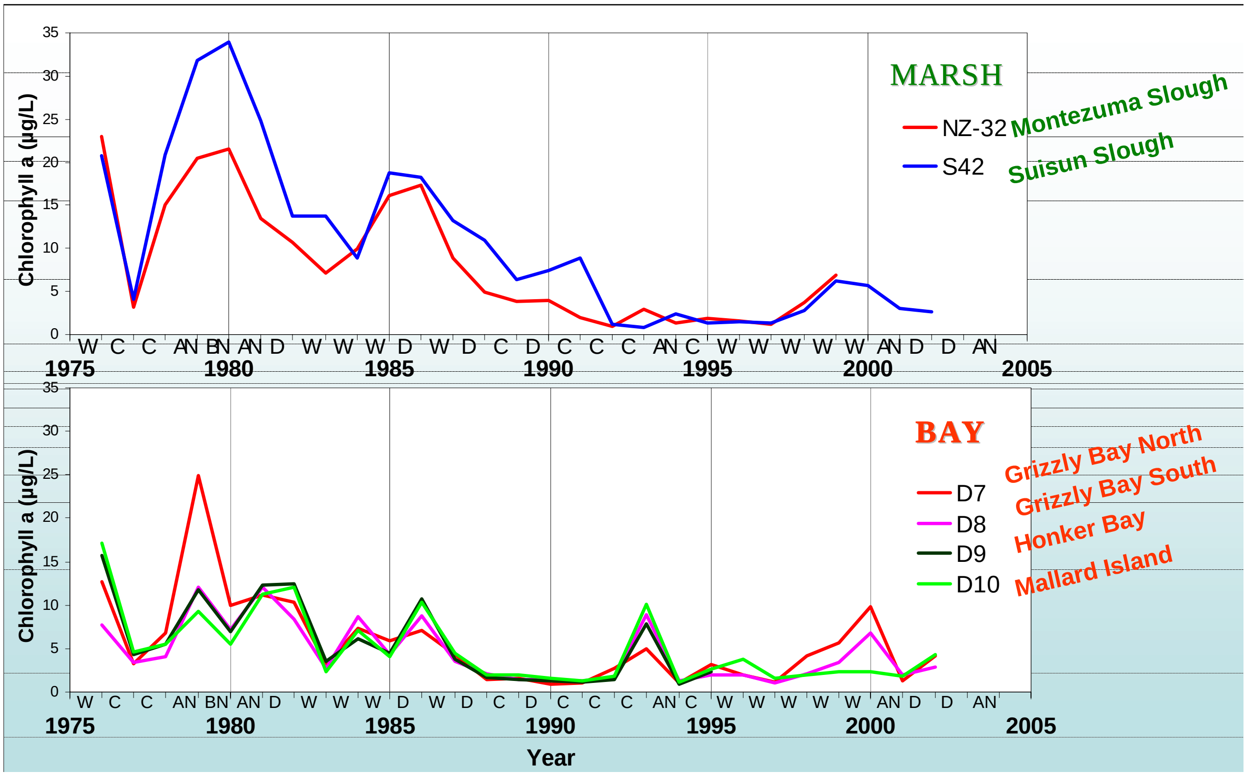


Figure 32. Spring chlorophyll *a* declines in Suisun Marsh and Bay stations. (Source: A. Mueller-Solger.)

Zooplankton . Zooplankton are microscopic or barely macroscopic animals (mostly crustaceans) that graze on phytoplankton and are, in turn, fed upon by larger organisms including larval and juvenile fish - i.e. an intermediate level in the food chain. Mueller-Solger presented data showing that several zooplankters in marsh channel sampling sites had declined during the period 1972-2001. She also presented data from Mueller-Solger et al. (2002) showing higher zooplankton growth potential in small marsh sloughs compared to Delta river channels and speculated that these small marsh sloughs may provide refugia with higher phytoplankton biomass and more edible organic carbon than larger channels and other areas of the estuary. Organic carbon is a product of plant and animal growth and decomposition in the marsh channels and planes. It occurs in the form of dissolved molecules (the "bog brew") and particles (the "swamp stew"). Some organic carbon is easily metabolized ("bioavailable") and an important foodweb component. In the last part of her talk, Mueller-Solger presented data from Sobczak et al. (2002) that showed that total and bioavailable dissolved and particulate organic carbon were higher in Cutoff Slough than in sites in the Delta and its inflows. Although not entirely clear from the available data, it appears that Suisun Marsh channels, especially the smaller sloughs, may provide a richer food base than sites in the Sacramento-San Joaquin Delta.

Larger Invertebrates. The difference between these organisms and zooplankton is somewhat arbitrary and is made in this case because these invertebrates are large enough to be captured in the same otter trawl UC Davis researchers use to sample fish in the marsh. These organisms can be predators or prey. Schroeter divided them further into two groups:

- Large shrimp of the genera *Crangon*, *Palaemon* and *Exopalaemon*.
- Macrozooplankton of the genus *Neomysis* and *Acanthomysis*

The abundance of *Crangon franciscorum* has fluctuated rather widely over the period of record with no particular trend (Figure 33). On the other hand *Palaemon macrodactylus* abundance was particularly low during the 1990s. In 2001 a new shrimp, the Siberian prawn (*Exopalaemon modestus*) began to dominate the catches. Given its size and abundance, the new shrimp is probably playing an important role in the foodweb, but its role has not yet been defined.

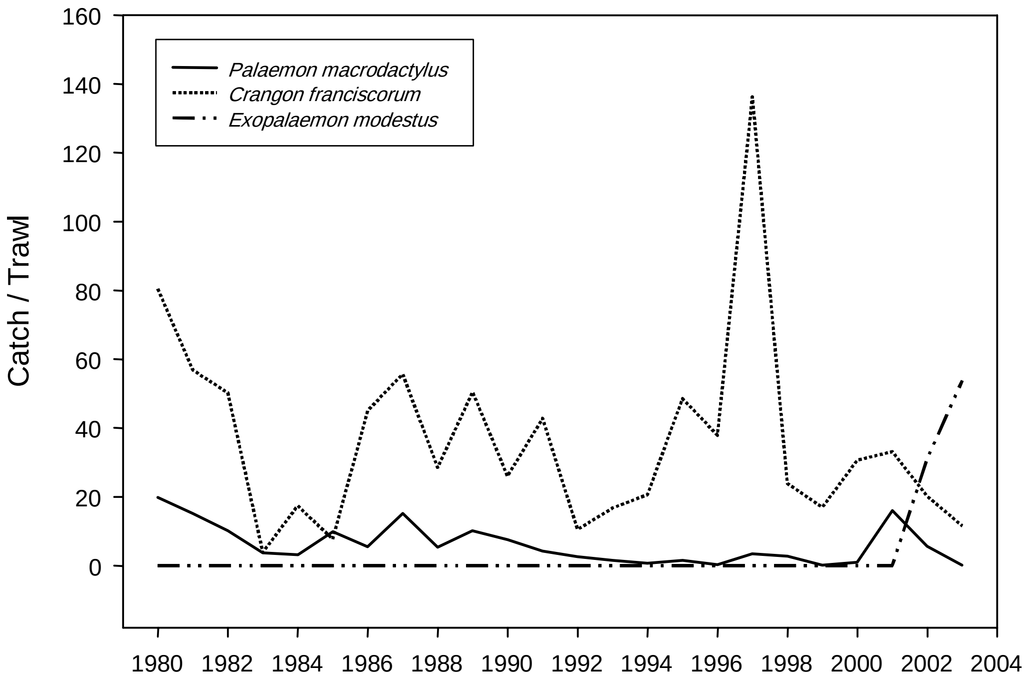


Figure 33. Otter trawl catches of large shrimp in Suisun Marsh, 1980–2003. (Source: R. Schroeter.)

The native mysid, *Neomysis mercedis* has been in decline in much of the estuary (Figure 34) but in some regions is being replaced by introduced mysids such as *Acanthomysis bowmani*. In Suisun Marsh, otter trawls continue to capture *N. mercedis* but also the aliens, *N. kadakensis* and *A. bowmani* (Figure 35). In Suisun and Montezuma sloughs, spring sampling in 2000 captured few *N. mercedis* or *A. bowmani* but large numbers of *N. kadakensis* (Figure 36).

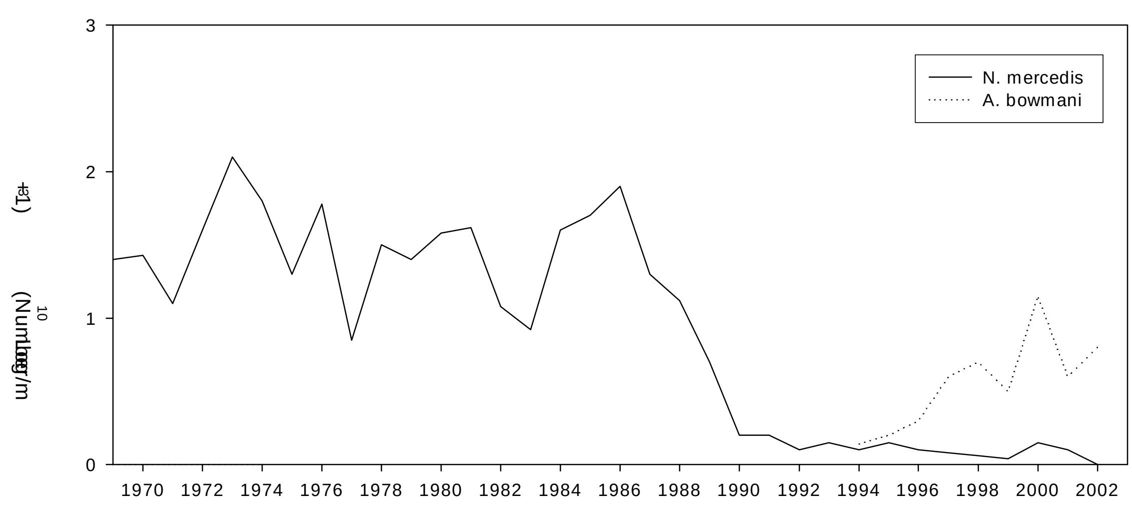


Figure 34. Spring abundance of mysids in Suisun Marsh, 1969–2003. (Source: R. Schroeter.)

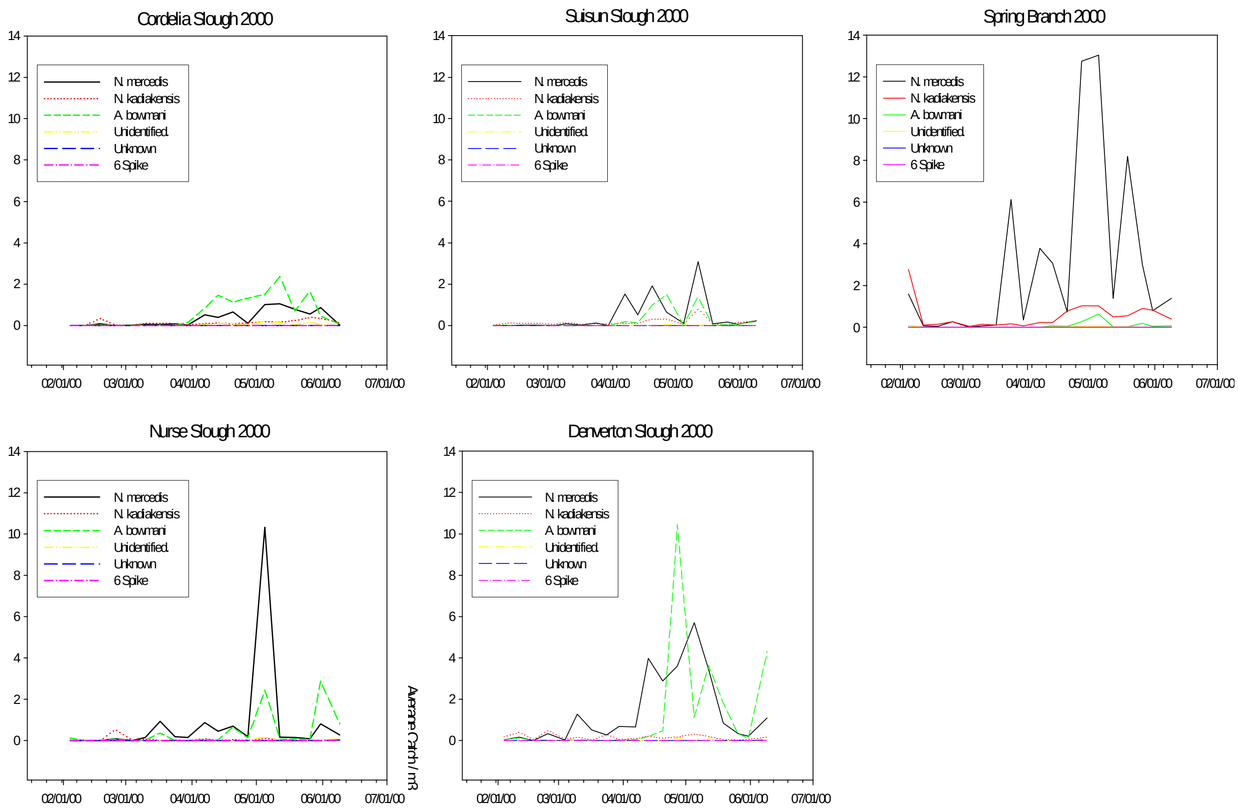


Figure 35. Macrozooplankton in Suisun Marsh sloughs. (Source: R. Schroeter.)

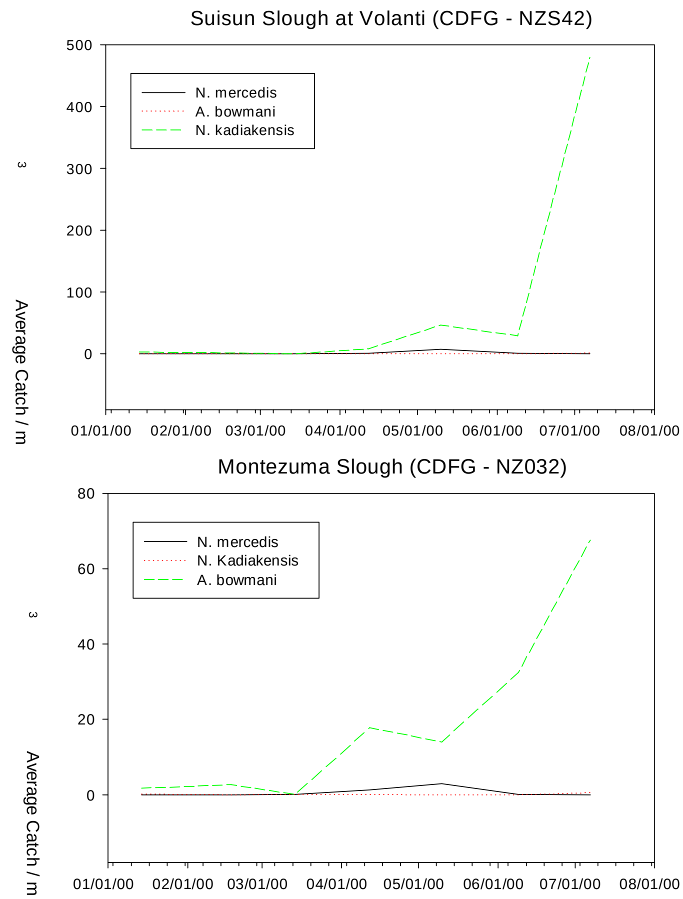


Figure 36. Macrozooplankton in Montezuma and Suisun sloughs. (Source: R. Schroeter.)

One of the take home messages from the zooplankton and mega shrimp data is the ever changing nature of the aquatic foodweb in Suisun Marsh and the remainder of the San Francisco Estuary. As reported by Cohen and Carlton (1998), the San Francisco Estuary is one of the most invaded in the world. The shrimp, benthos, and fish data (below) indicate that the invasions are continuing.

Benthos. Schroeter presented some preliminary 2004 data on the numbers of benthic invertebrates found at several sites in Suisun Marsh channels. The CALFED funded study included 30 individual sites with samples taken at 25%, 50%, and 75% of the channel width. Only the mid-channel data were reported.

I only show abundance data for two organisms found at the various sites - the overbite clam (*Potamocorbula amurensis*) (Figure 37) and a group of organisms collectively known as oligochaetes (Figure 38). I selected these organisms because the overbite clam is an alien species that may have dramatically changed the foodweb in the San Francisco estuary (Kimmerer and Orsi 1995) and the oligochaetes are common organisms in the Suisun Marsh benthic community and are important dietary components of some marsh fish (Feyrer 1999). The data indicate that the overbite clam in most common in the western marsh and the oligochaetes are also most common in the western marsh but in the smaller channels but with an overall wider distribution. It must be kept in mind that these data are from mid-channel only and for one year.

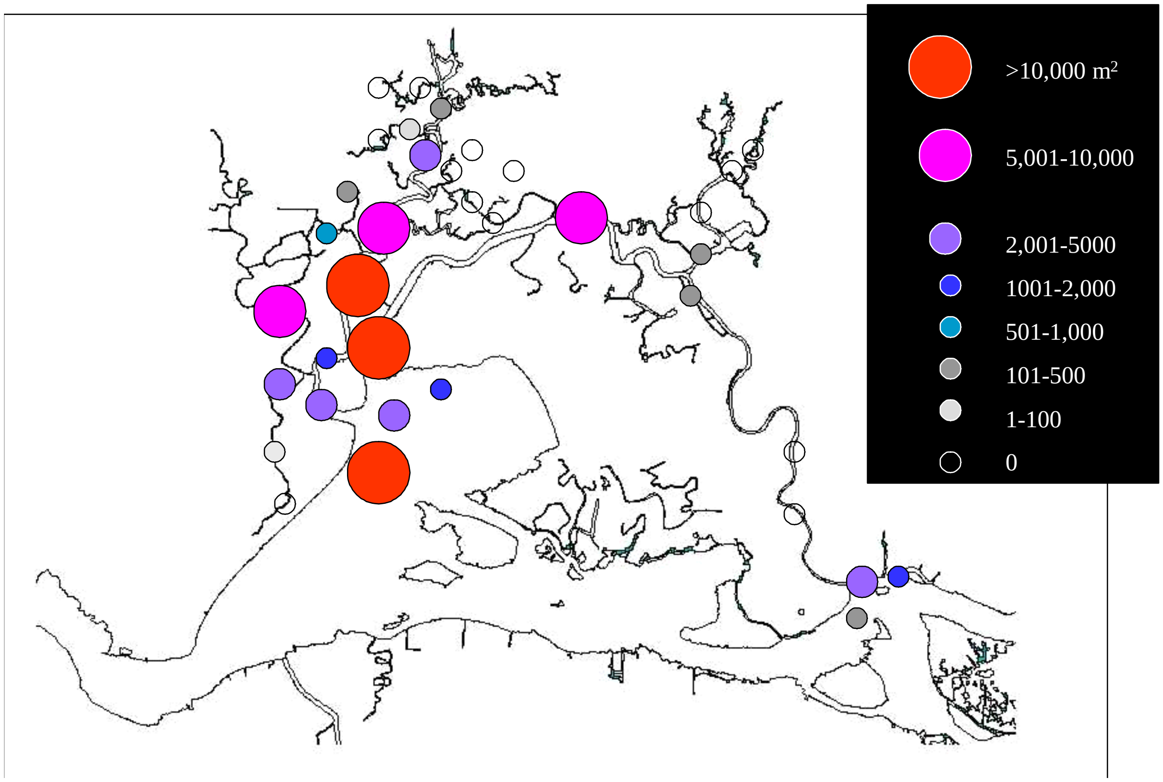


Figure 37. Overbite clam abundance in Suisun Marsh channels. (R. Schroeter.)

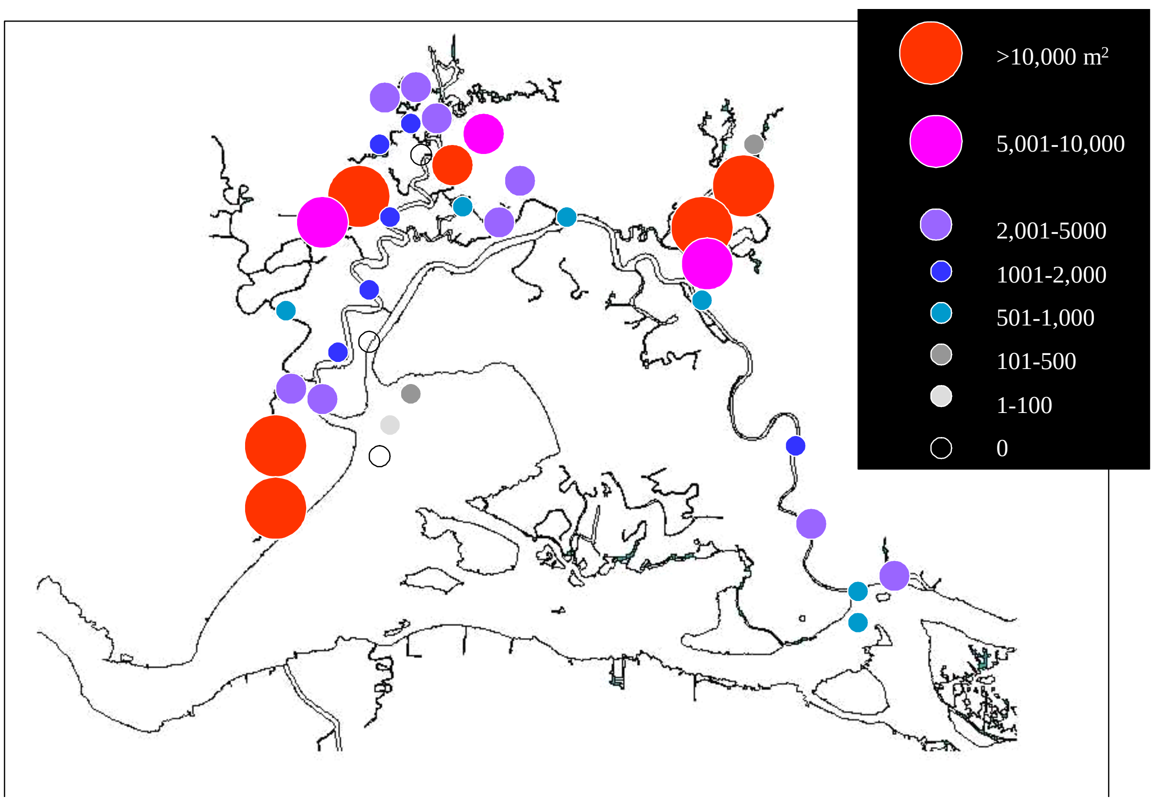


Figure 38. Oligochaete distribution in Suisun Marsh channels. (Source: R. Schroeter.)

Schroeter ended his presentation with following tentative conclusions:

1. Shrimp
   a. The community continues to change. The newly introduced Siberian prawn may be assuming an important role in the foodweb.
2. Macrozooplankton
   a. Native mysid shrimp continue to decline or remain at low abundance.
   b. There may be refugia for native mysids in the smaller channels
3. Benthos
   a. Preliminary data indicate local hotspots in species richness and abundance.
   b. Overbite and Asian (*Corbicula fluminea*) clams are restricted in distribution.
   c. The benthic community is largely dominated by filterers and collectors.
4. Overall
   a. The marsh appears to be a very productive system.
   b. The invertebrate community is very diverse and consists of native and alien animals.

Fish. Suisun Marsh has a very diverse fish assemblage (Table 8, from Matern et al. 2002 - an excellent reference those interested in learning more about Suisun Marsh fishes.) Among the species found in marsh channels are three native species that are listed as endangered or threatened - winter Chinook (state and federal endangered), spring Chinook (state and federal threatened), steelhead rainbow trout (federal threatened) and delta smelt (state and federal threatened). Another native fish, the Sacramento splittail, was a federally listed threatened species until early in 2004 when the USFWS delisted the species. Protecting these native fish has dramatically influenced Suisun Marsh management, from operation of the salinity control gates to moving water onto the duck clubs for waterfowl management and leaching salts from the soil profile.

Table 8. Fishes collected from May 1979 to December 1999 using an otter trawl and beach seine in Suisun Marsh, California, listed in decreasing order of abundance in the trawl. The principal environment of each species is coded as follows: A = anadromous, E = estuarine, F = freshwater, M = marine. An asterisk (*) denotes native species. From Matern et al. 2002.

		Otter Trawl		*Beach Seine*		*Principal Environ-ment*
Species	*Code*	*Number*	*%*	*Number*	*%*	
Striped bass *Morone saxatilis*[a]	SB[b]	46,125	36	5,497	12	E
*Threespine stickleback *Gasterosteus aculeatus*[a]	STBK	13,128	10	1,955	4	F, E
Yellowfin goby *Acanthogobius flavimanus*[a, c]	YFG	12,470	10	8,551	19	E, M
*Tule perch *Hysterocarpus traski*[a]	TP	11,069	9	817	2	F, E
*Sacramento splittail *Pogonichthys macrolepidotus*[a]	ST	10,770	8	1,358	3	E
*Longfin smelt *Spirinchus thaleichthys*[a, c]	LFS	7,514	6	20	< 1	E
*Prickly sculpin *Cottus asper*[a]	PSCP	7,017	6	311	1	F, E
Shimofuri goby *Tridentiger bifasciatus*[a, d, e]	SG	6,044	5	698	2	E
Common carp *Cyprinus carpio*[a, e]	CP	2,732	2	250	1	F

Table 8. Fishes collected from May 1979 to December 1999 using an otter trawl and beach seine in Suisun Marsh, California, listed in decreasing order of abundance in the trawl. The principal environment of each species is coded as follows: A = anadromous, E = estuarine, F = freshwater, M = marine. An asterisk (*) denotes native species. From Matern et al. 2002. (Continued)

		Otter Trawl		*Beach Seine*		*Principal Environ-ment*
Species	*Code*	*Number*	*%*	*Number*	*%*	
*Sacramento sucker *Catostomus occidentalis*[c]	SKR	2,114	2	72	< 1	F
*Pacific staghorn sculpin *Leptocottus armatus*[a, c]	STAG	1,630	1	1,704	4	M
Threadfin shad *Dorosoma petenense*[a]	TFS	1,369	1	1,180	4	F
*Starry flounder *Platichthys stellatus*[a, c]	SF	1,302	1	213	< 1	M
White catfish *Ameiurus catus*[a]	WCF	1,038	1	71	< 1	F
*Delta smelt *Hypomesus transpacificus*[a]	DS	442	< 1	69	< 1	E
Inland silverside *Menidia beryllina*	ISS	335	< 1	21,843	47	F, E
American shad *Alosa sapidissima*[a]		263	< 1	24	< 1	A
Black crappie *Pomoxis nigromaculatus*[e]		235	< 1	10	< 1	F
*Northern anchovy *Engraulis mordax*		224	< 1	0	0	M
*Pacific herring *Clupea harengeus*		208	< 1	54	< 1	M
Goldfish *Carassius auratus*		162	< 1	11	< 1	F
Channel catfish *Ictalurus punctatus*[a]		123	< 1	6	< 1	F
*Hitch *Lavinia exilicauda*		99	< 1	13	< 1	F
*Sacramento pikeminnow *Ptychocheilus grandis*		96	< 1	85	< 1	F
Black bullhead *Ictalurus melas*		90	< 1	2	< 1	F
White crappie *Pomoxis annularis*		88	< 1	0	0	F
*White sturgeon *Acipenser transmontanus*		43	< 1	0	0	A
*Pacific lamprey *Lampetra tridentata*		38	< 1	0	0	A
*Chinook salmon *Oncorhynchus tshawytscha*[e]		34	< 1	183	< 1	A
Brown bullhead *Ictalurus nebulosus*		19	< 1	0	0	F
Fathead minnow *Pimephales promelas*		16	< 1	23	< 1	F
Bigscale logperch *Percina macrolepida*		15	< 1	5	< 1	F
Western mosquitofish *Gambusia affinis*		15	< 1	215	< 1	F
Rainwater killifish *Lucaina parva*		15	< 1	24	< 1	E
*Sacramento blackfish *Orthodon microlepidotus*		15	< 1	78	< 1	F
*Shiner perch *Cymatogaster aggregata*		14	< 1	0	0	M
Bluegill *Lepomis macrochirus*		11	< 1	12	< 1	F
*Plainfin midshipman *Porichthys notatus*		10	< 1	0	0	M
*California halibut *Paralichthys californicus*		3	< 1	0	0	M
Green sunfish *Lepomis cyanellus*		3	< 1	2	< 1	F
Golden shiner *Notemigonus crysoleucas*		3	< 1	2	< 1	F
*Green sturgeon *Acipenser medirostris*		3	< 1	0	0	A
*Rainbow trout *Oncorhynchus mykiss*		3	< 1	2	< 1	A
*Speckled sanddab *Citharichthys stigmaeus*		3	< 1	0	0	M
*Bay pipefish *Syngnathus leptorhynchus*		2	< 1	0	0	M
Redear sunfish *Lepomis microlophus*		2	< 1	0	0	F

Table 8. Fishes collected from May 1979 to December 1999 using an otter trawl and beach seine in Suisun Marsh, California, listed in decreasing order of abundance in the trawl. The principal environment of each species is coded as follows: A = anadromous, E = estuarine, F = freshwater, M = marine. An asterisk (*) denotes native species. From Matern et al. 2002. (Continued)

		Otter Trawl		*Beach Seine*		*Principal*
Species	*Code*	*Number*	*%*	*Number*	*%*	*Environ-ment*
*Surf smelt *Hypomesus pretiosus*		2	< 1	0	0	M
Shokihaze goby *Tridentiger barbatus*		1	< 1	0	0	E
*Longjaw mudsucker *Gillichthys mirabilis*		1	< 1	0	0	E, M
*Pacific sanddab *Citharichthys sordidus*		1	< 1	0	0	M
Wakasagi *Hypomesus nipponensis*		1	< 1	1	< 1	F, E
*White croaker *Genyonemus lineatus*		1	< 1	0	0	M
Warmouth *Lepomis gulosus*		1	< 1	0	0	F
Largemouth bass *Micropterus salmoides*		0	0	2	< 1	F

a. Species collected in all 10 sloughs.

b. SB-J denotes “juveniles” (<150 mm), SB-A denotes “adults” (> or = 150 mm).

c. Collected in significantly greater abundance in Suisun Slough seines.

d. Identified as chameleon goby *Tridentiger trigonochephalus* in Meng et al. (1994) but later shown to be shimofuri goby (Matern and Fleming 1995).

e. Collected in significantly greater abundance in Denverton Slough seines.

The following description of the Suisun Marsh fish community is based on Peter Moyle’s presentation at the workshop and the Matern et al. (2002) paper.

DWR began funding the UC Davis fish studies in 1979 with the general goal of assessing the effects of Suisun Marsh protection measures on the fish community. Over the course of the study, the goals have expanded to determine:

- What regulates fish abundance?
- What are the long-term trends in fish abundance?
- Do native and introduced fish populations behave differently?
- Are there predictable fish assemblages?

Moyle emphasized that the study is designed to examine the ecology of the entire fish community.

The UC Davis researchers used otter trawls to collect monthly fish samples at nine sites in Suisun Marsh sloughs (Figure 39). They also sampled two sites with a beach seine to pick up those fish not routinely captured in the bottom sampling gear - juvenile Chinook salmon, for example. Environmental data were collected with the tows - Secchi disk depth (light penetration), specific conductance (salinity), dissolved oxygen, and temperature.

As shown in Figure 40, the brackish, mid-estuary nature of Suisun Marsh results in two major pools from which Suisun Marsh fishes may be drawn - the marine/estuarine species pool and the freshwater species pool. The resulting marsh species pool contains 54 species - 25 of which are non-native. There are 28 fish species commonly found in marsh channels, of which 14 are alien. The 16 most abundant species listed in Table 8 accounted for more than 99% of the catch, with nine of these species being native.

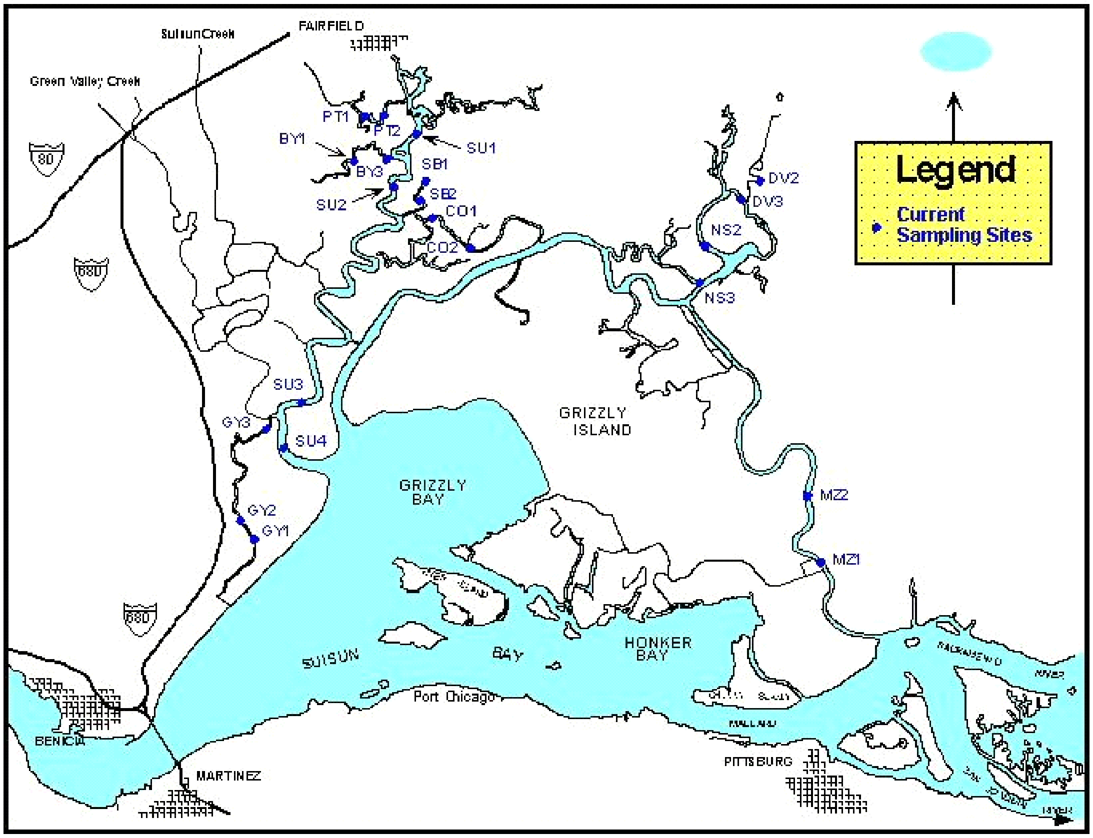


Figure 39. UC Davis fish sampling sites in Suisun Marsh. (Source: P. Moyle.)

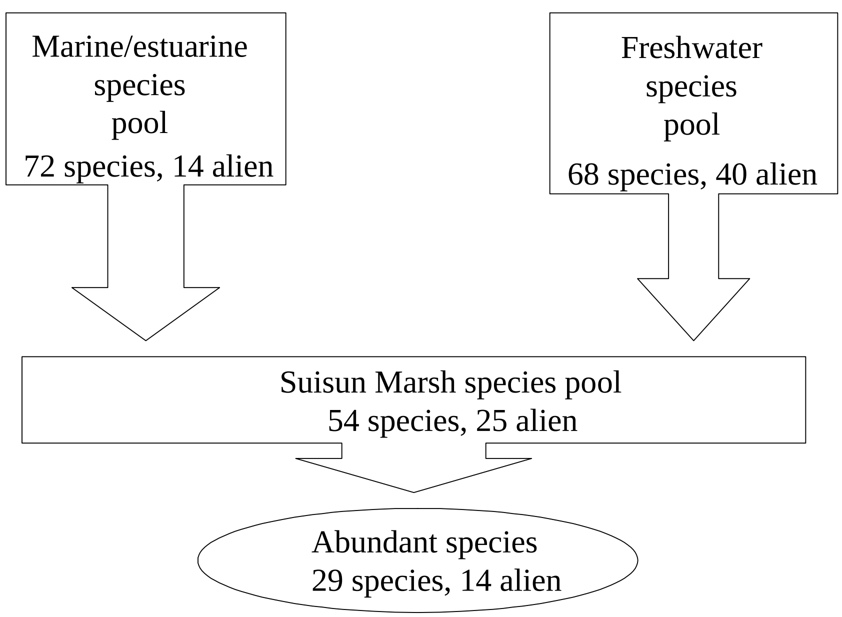


Figure 40. Fish pools from which the Suisun Marsh fish population is drawn. (Source: P. Moyle.)

The fish abundance trend data are summarized in Figure 41, along with some important events that occurred during the two plus decades of sampling. (Note that the overbite clam is called the asian clam and is the recently introduced Siberian prawn, *Exopalaemon modestus*.) Overall both native and alien fish communities in Suisun Marsh have declined during the period of record. Although there was some resurgence after the 1987-1992 drought, the total fish catch did not return to their pre-drought levels. The overall fish abundance trends found in the marsh are similar to those found by others in the upper estuary (e.g. Bennett and Moyle 1995) following the drought. The similar trends do not mean that fish in separate parts of the estuary are being regulated by similar causes.

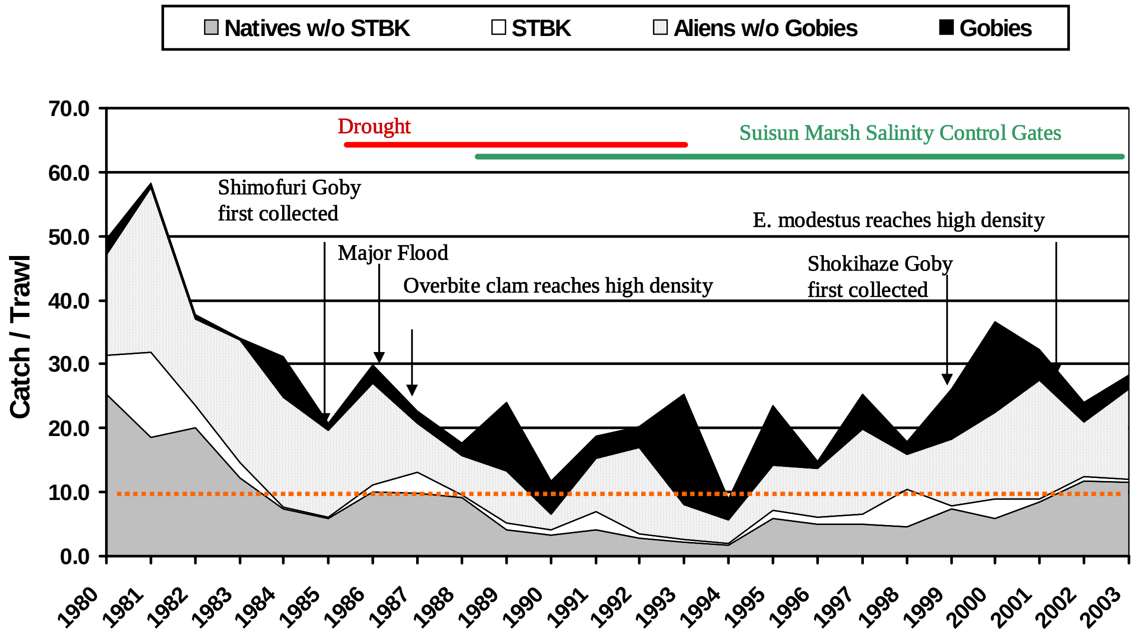


Figure 41. Trends in annual Suisun Marsh fish catches, 1980–2003. (Source: P. Moyle.)

Moyle postulated that the following factors may limit Suisun Marsh fish abundance and distribution:

- Recruitment from outside the marsh.
- Water quality within the marsh, in particular dissolved oxygen sags in some channels when clubs are drained (see section on dissolved oxygen problems, below)
- Habitat quality, including structural complexity.
- Invasions
- Species specific factors - for example, food supply to species or life stages as the supply is affected by droughts and the effects of new species (the overbite clam)

Matern et al. (2002) observed that operation of the salinity control gates did not have any obvious effects on catches.

Moyle concluded by showing three very general conceptual models of food webs in the marsh - an overall aquatic food web (Figure 42), a pond food web (Figure 43), and a benthic food web (Figure 44). These conceptual models show the general pathways of materials and energy in the system and are developed further later on in this report.

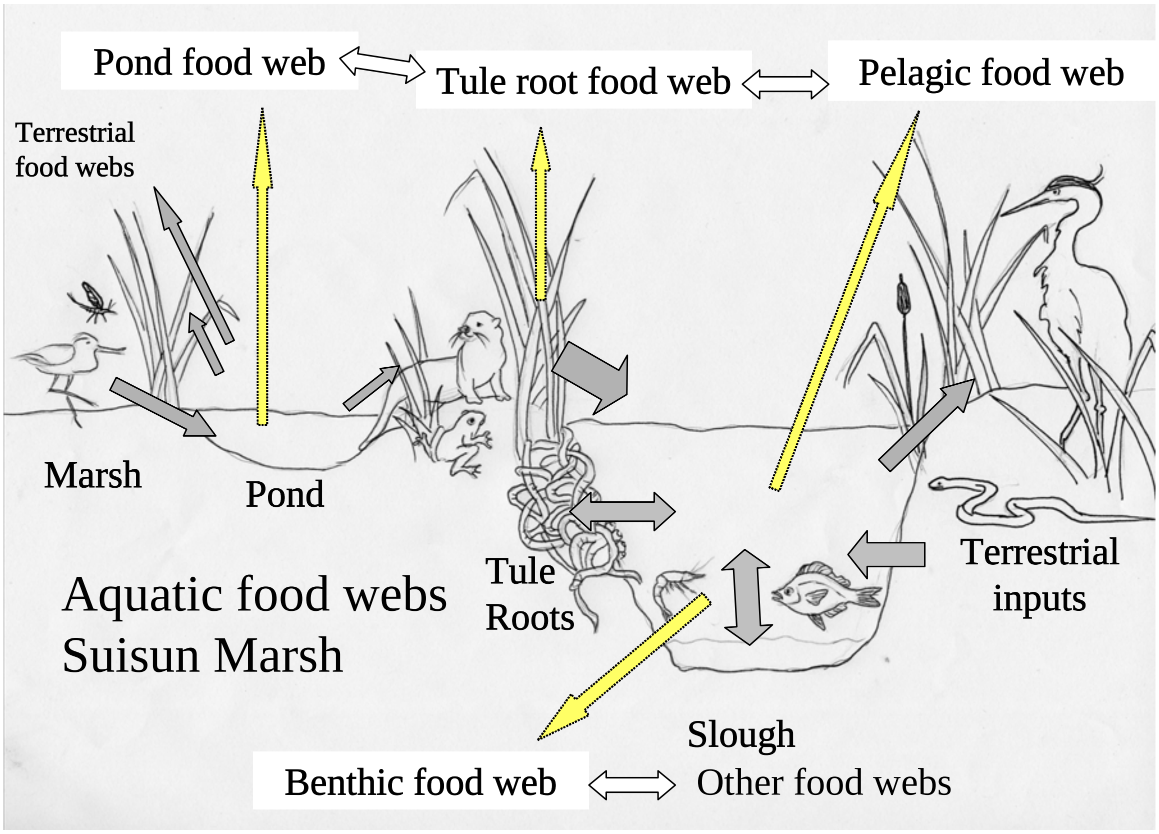


Figure 42. Conceptual model of aquatic food webs in Suisun Marsh. (Source: P. Moyle.)

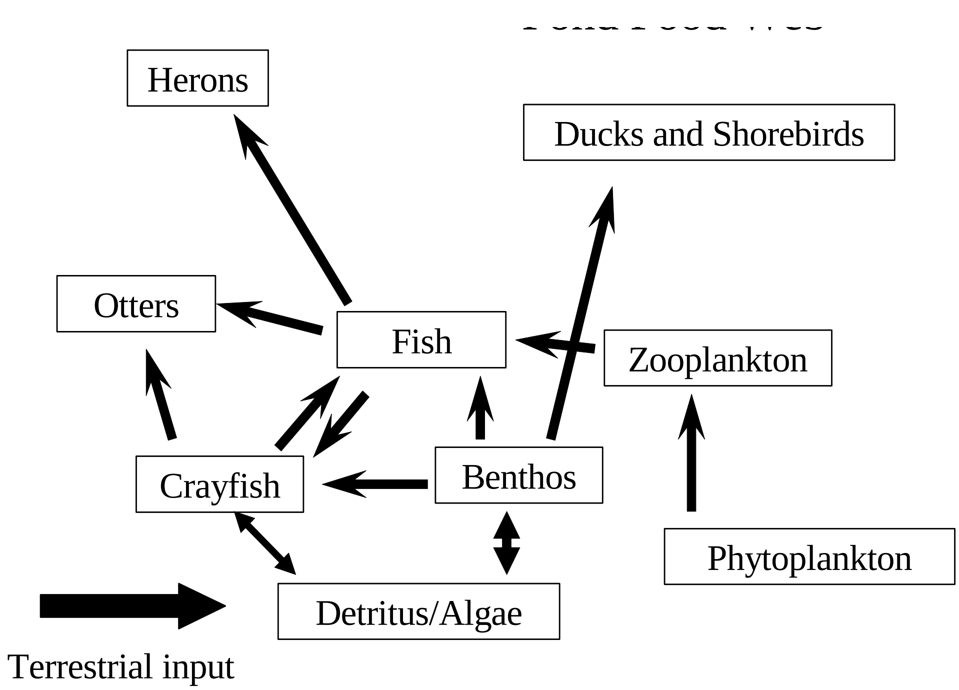


Figure 43. Conceptual model of pond food webs in Suisun Marsh. (Source: P. Moyle.)

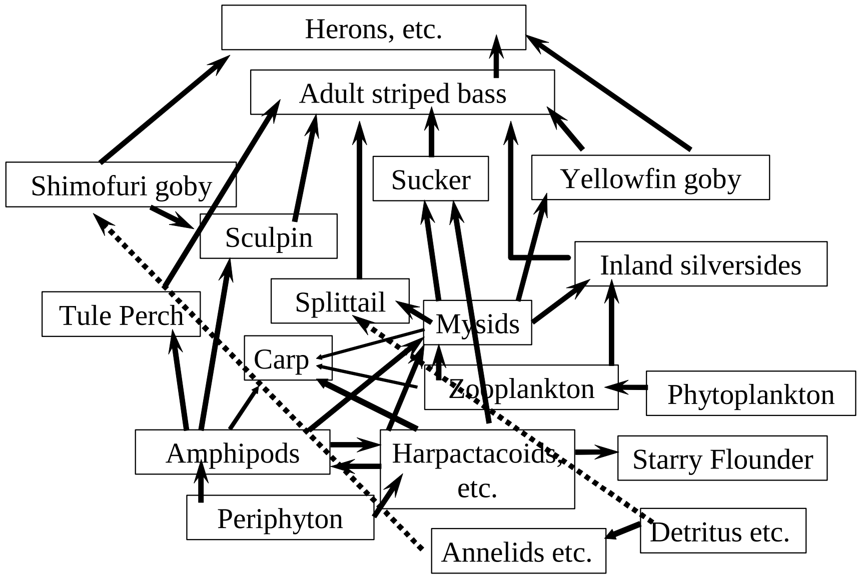


Figure 44. Conceptual model of benthic food webs in Suisun. (Source: P. Moyle.)

Dissolved Oxygen Problems in Suisun Marsh Channels . As explained by Schroeter, UC Davis field crews noted low dissolved oxygen concentrations during some of their sampling cruises. Fish mortality was also observed, along with reduced abundance of some organisms. The dissolved oxygen depressions, called sags, seemed to coincide in time and space with pond discharge and flood up activities.

Figure 45 illustrates the dissolved oxygen problem as measured at two stations in Boynton Slough for the period 2000 through 2003. The 5 mg/l level is often used as a fish protection threshold below which dissolved oxygen levels should not fall. The data demonstrate that dissolved oxygen levels were at or near this threshold on several occasions during the three-year period - often for extended lengths of time. With the exception of Nurse and Montezuma sloughs, similar problems were noted at other sampling stations.

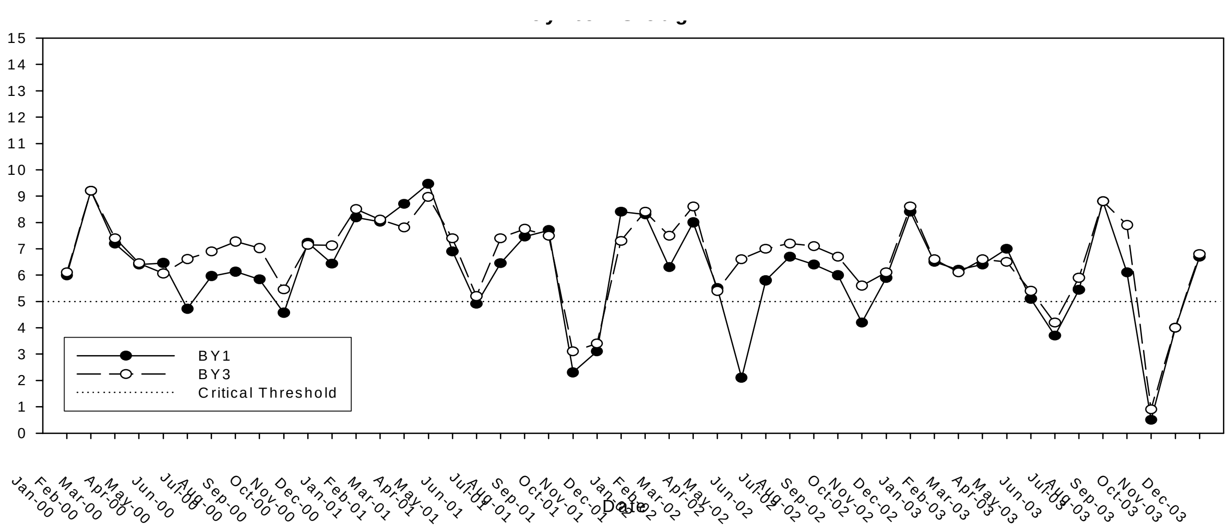


Figure 45. Dissolved oxygen concentrations in Boynton Slough, 2000–2003. (Source: R. Schroeter.)

Discussion - Biological Processes and Conceptual Models

Frank Wernette led the discussion on biological processes and species in Suisun Marsh. As with the previous discussions, below are what I believe the main points to have come out of the discussion and Q&A.

- It is important to understand interactions between different system components, e.g. the role of mammals in the marsh.
- Managers need to keep the potential effects of sea level rise in mind and how the marsh and estuary may look with more levee breaches.
- The fish community in Suisun Marsh will continue to evolve in complex, interesting, and somewhat unpredictable ways.
- Introduced species have, and will, play an important role in the marsh. Although we have to pretty much live with what has already arrived, new controls (on ballast water, for example) may reduce future introductions. Pepperweed is an example of how land management practices (e.g., disking) may encourage the spread of an introduced plant. The plant itself is tall and may shade out more desirable native plants. Our conceptual models of the marsh must include introduced species - in particular where their habitat requirements (niches) overlap or affect listed species.
- Waterfowl feeding models need to be energetically driven and include the role of seeds and invertebrates in meeting the birds' energy needs.
- Waterfowl scientists must consider local, regional and national perspectives. Changing habitat conditions in the breeding grounds, the Central Valley and Suisun Marsh affect the kinds and numbers of birds using the marsh, as well as hunting opportunities.
- There is an indication that waterfowl populations in the marsh were already depressed by the early1970s. Programs aimed at restoring these populations to early 1900 levels may not be appropriate.
- We have little information on the value of tidal wetlands for waterfowl production. The scientific methods are available but the data largely have not been collected.
- Duck club owners are interested in restoration and cooperating with scientists. The club owners have goals of their own - i.e. to grow and attract more birds to ensure good hunting opportunities for members. The duck clubs are components of the marsh and the owners are willing to work towards creating a more ecologically stable system.
- The seasonal dissolved oxygen levels observed in some channels are serious enough to be of concern to fish managers and biologists.
- Overall the marsh contains valuable habitat and supports diverse plant and animal communities.
- Suisun Marsh will always contain a mix of wetland types, and will have a strong management component.

Climate Change and Suisun Marsh

Michael Dettinger (USGS) described some aspects of the potential effects of on climate change on the estuary in his presentation titled “Climate change and freshwater inflows in the 21st Century - What are the models trying to tell us?” Much of the material in the following discussion is taken from Dettinger’s presentation, supplemented with information from papers cited in his discussion and the open literature.

Scientists have been actively discussing climate change and it effects for the past few decades, with the conceptual model built around increased emission of carbon dioxide resulting from burning fossil fuels. Carbon dioxide gases cause heat to be trapped in the lower atmosphere, accompanied by a rise in air temperatures. Although the increase in emissions has been well documented (Levitus et al. 2001), United States and California policymakers have not always agreed on the meaning of the increased emissions and what should be done about them. For example, the most recent California Water Plan (DWR Bulletin 160-98) did not consider global climate change in planning for California’s water future - or considered it by omission. That this attitude may be changing is the extensive reference to climate change in the latest water plan update (Bulletin 160-03) to be released later in 2004.

Over the past century the San Francisco Estuary has experienced a gradual sea level rise. The rise varies from location to location along the coast but the average sea level in San Francisco Bay has risen an estimated 5 inches and may rise another 13 to 19 inches by 2100 (M. Dettinger, USGS, personal communication). To these historically observed sea level rises will be added rises that are due to climate change. This combination could bring the total rise from 1900 to 2100 from about 10 inches (no climate-change effect) to as much as 40 inches - i.e., about 5 inches in the 20th century plus about 5 inches continuation of historic rise in the 21st century plus about 30 inches in the 21st Century due to global warming (high end Intergovernmental Panel on Climate Change estimate).

Climate change has the potential to affect the amount and timing of stream flows and thus the amount of water reaching the estuary. As early as the 1980s Roos (1989) observed that the snow level appeared to be rising in the Sierra and that the rise could dramatically affect runoff. These data are particularly important in California’s water management system - a system that is based on using the snow pack and large artificial reservoirs to store water until it is needed for use by agricultural, urban and industrial users. The large man-made reservoirs are in turn operated on annual cycle involving maintaining storage capacity through the winter months for flood management and filling the reservoirs during the spring snow melt. Changes to increased winter rains and less snowmelt can have dramatic effects on amount and timing of runoff from the Sierra Nevada and reservoir operation.

The following discussion is adapted from Dettinger’s presentation and I have used four of his slides to convey his message. Where possible, I have also included references where the original slides and additional information can be found.

Several models use the projected emissions to arrive at predictions for temperature increases over the next century. The computational process and information needs vary among models and thus the temperature predictions will be expected to vary as well. Figure 46 (top panel) shows the range of predicted temperature increases from several models - a relatively narrow range of 2-6 degrees C considering the complexity of the task. The bottom line is that our current understanding of emissions and climate modeling all predict significant air temperature increases over the next century.

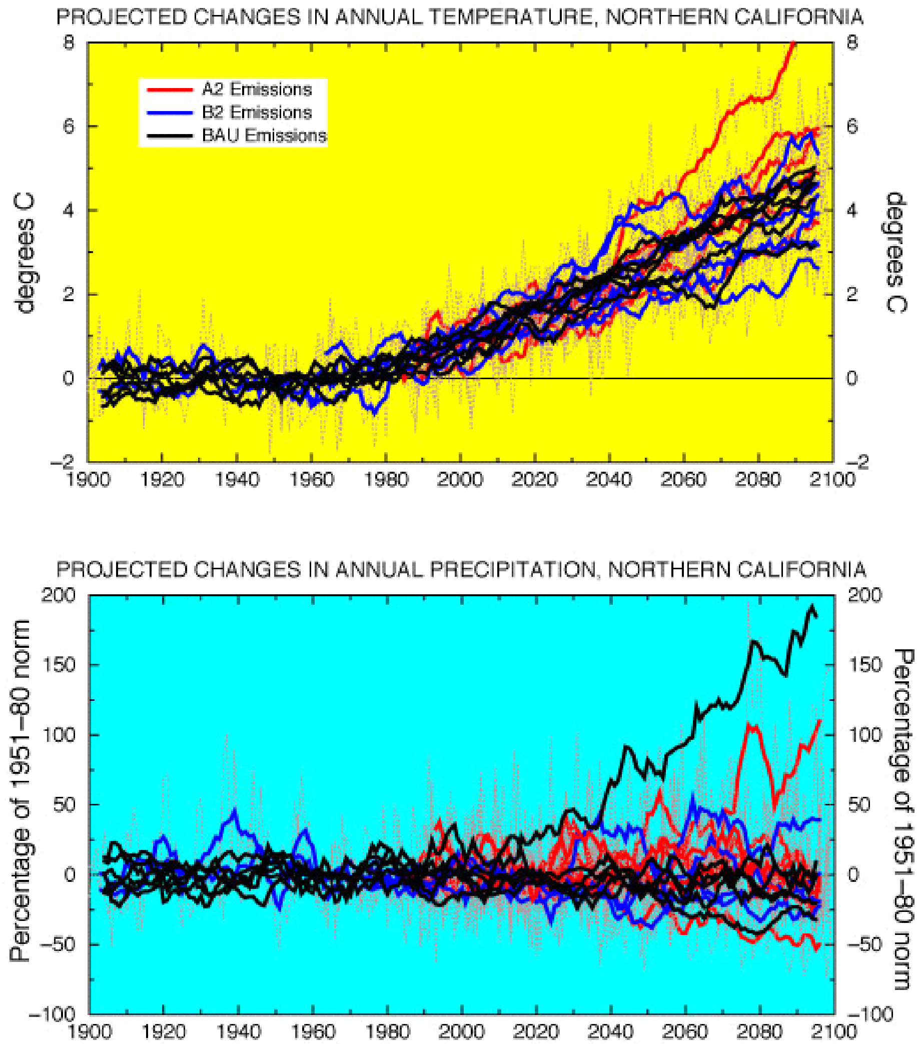


Figure 46. Predicted Northern California temperature (top panel) and total precipitation changes. (Source: M. Dettinger.)

Moving from predicting temperature to effects on total precipitation adds another layer of complexity and effects on precipitation will vary from place to place. For Northern California, there is a fairly broad range in the predicted changes in precipitation, but current projections mostly indicate that there may be relatively little change in total precipitation (Figure 46, bottom panel). Due to overall warmer temperatures, the annual snow and rain patterns in Northern California are likely to change, with generally less winter snowpack and more winter rain (Figure 47 from Knowles and Cayan 2004). These seasonal changes in precipitation pattern will influence estuarine salinity regimes, with generally lower than average historic salinities in the winter and higher salinities in the spring through fall (Figure 48 from Knowles 2001).

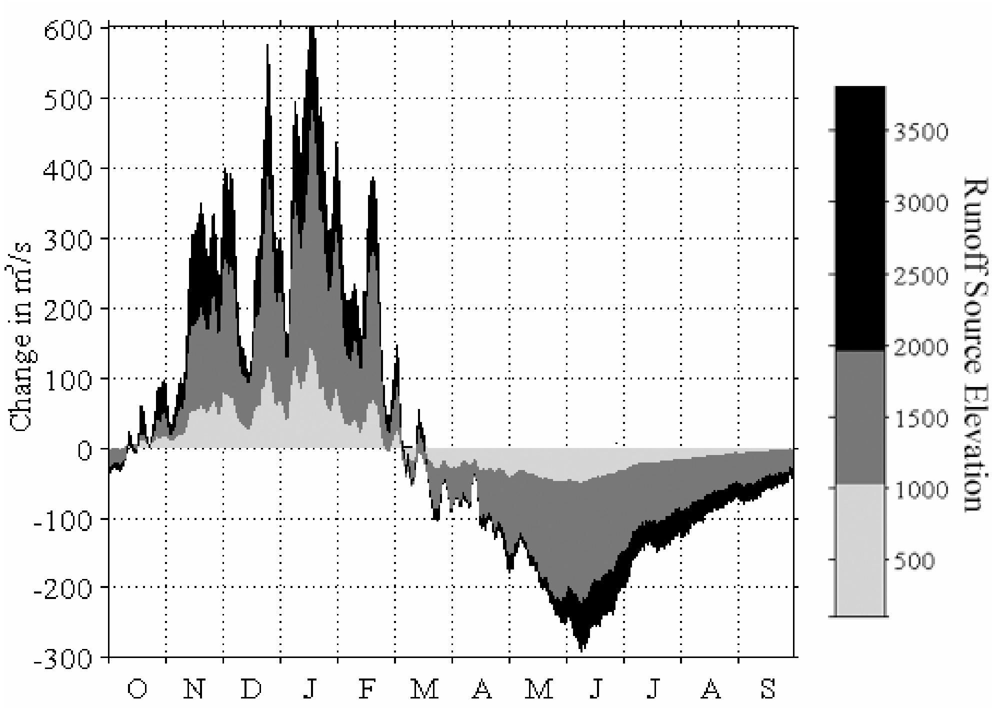


Figure 47. Projected changes in freshwater flow to San Francisco Bay. (Source. M. Dettinger.)

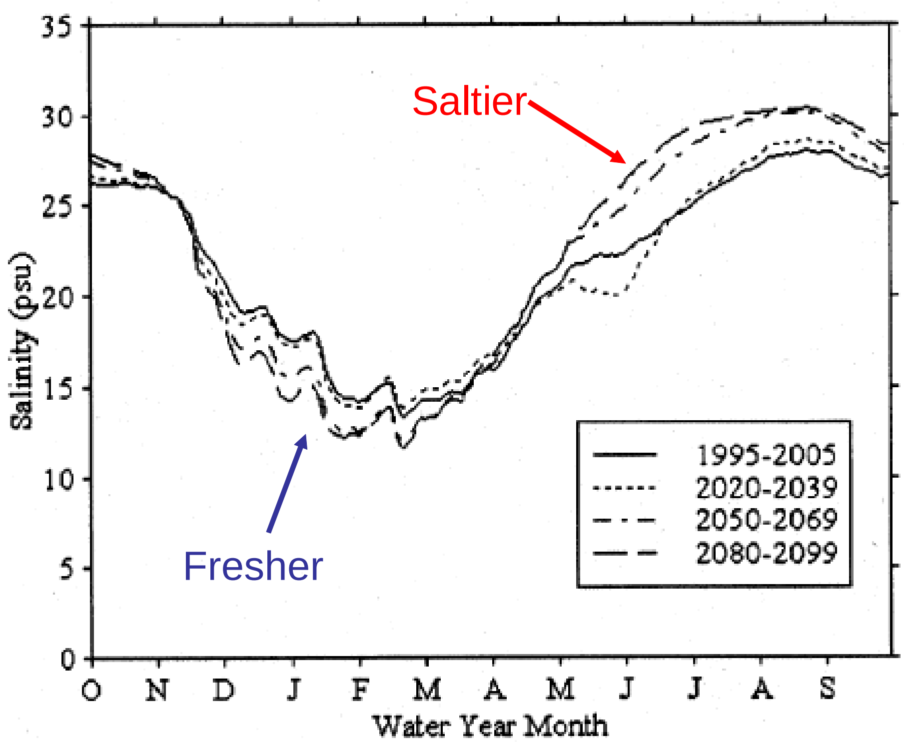


Figure 48. Simulated San Pablo Bay salinities. (Source: M. Dettinger.)

The climate change scenarios described by Dettinger emphasized the need for water and resource managers to revise their conceptual models of how freshwater flows affect the estuary - and how to cope with increased winter flooding and providing water to California's cities and farms. Not only will the water levels in estuary rise over the next century, but also the freshwater flow patterns are expected to change dramatically as well. The issue is not if climate change is going to happen, but how we going to deal with it.

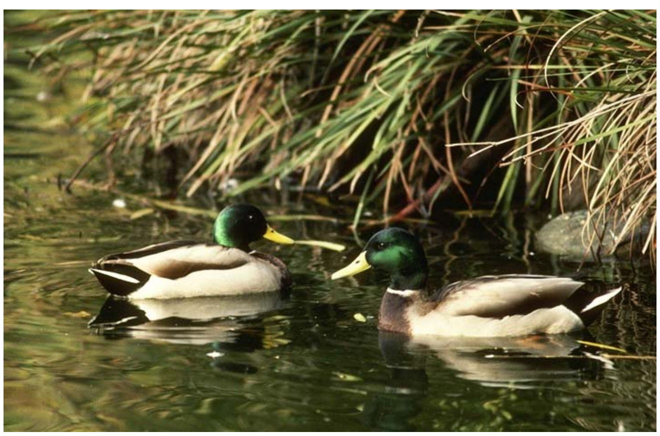
Managing Suisun Marsh

Managing Suisun Marsh is based on a series of legislative and administrative actions that provide the framework around which actions are taken to protect and preserve the marsh. Many of these actions began in the 1960s and the framework has evolved as managers, engineers and biologists learn more about the system and the range of management goals expands. For example, the state and federal endangered species acts have affected marsh management in many ways, from protecting rate marsh plants, birds that use the marsh and fish that inhabit marsh channels.

The following brief discussion of marsh management is based on presentations by Pete Chadwick and Victor Pacheco at the March workshop, supplemented by information from published reports. For a more complete description of the legislative and administrative environment, see CALFED (2000). I follow the workshop program by first describing marsh management roughly from the 1960s into the 1990s and then events occurring after about 2000.

Historic Perspective on Managing Suisun Marsh -- 1960s through mid-1990s

DFG and DWR began the Delta Fish and Wildlife Protection Study around 1960 with the specific goal of identifying potential effects of increased water diversion on fish and wildlife resources of the estuary. The impetus for this study came from plans for the State Water Project to begin diverting water from the Delta in the mid- to late-1960s. One of the study goals was to determine which areas would be of most concern, not only to determine where to focus additional studies, but which areas seem to offer the best possibility for measures to avoid or mitigate for impacts of SWP pumping. To provide a baseline against which changes could be compared, Skinner (1962) published a historical review of the estuary's fish and wildlife resources, including those of the Suisun Marsh.



Out of the Fish and Wildlife Protection studies, Suisun Marsh emerged as the area where operation of the SWP (and CVP) could seriously impact the estuary's wildlife resources. The rationale for this conclusion was roughly:

- Waterfowl use in Suisun Marsh was greater than that in Napa Marsh.
- Waterfowl resources were typically greater in brackish as compared to saline marshes.
- Alkali bulrush was the most important food in brackish marshes.
- Alkali seed production depended on soil salinity and flooding cycle.

The latter two points in the rationale came from studies by George et al. (1965) and Mall (1969) and resulted in the following hypothesis: *The primary wildlife need related to SWP (and CVP) operation is maintenance of water salinities needed to grow alkali bulrush and other associated brackish marsh plants in Suisun Marsh*.

The results of the findings and hypothesis were to use the following guidelines in marsh management:

- Protect Suisun Marsh from urban encroachment.
- Maintain status quo regarding the distribution of tidal and managed wetlands in the marsh.
- Have water of appropriate salinity available to manage brackish marsh habitat.
- Encourage owners of managed wetlands in the marsh to use best management practices.
- Provide alternate water supplies for some marsh lands bordering Suisun Bay.
- Mitigate for degradation of habitat on channel islands by enhancing inland marsh areas.

Table 9 contains a brief annotated chronology of events that have been integral to developing and implementing Suisun Marsh management plans. This list is expanded from the one presented by Pete Chadwick at the workshop and from a more complete chronology that can be found at http://iep.water.ca.gov/suisun/program/index.html.

From the 1960s through the mid-1990s, much of the management effort in Suisun Marsh focused on efforts to mitigate for the effects of the SWP and CVP on the salinity of water available to the private duck clubs and public lands in the marsh. Water quality and water rights hearings convened by the SWRCB resulted in a series of water quality standards designed to protect the marsh's beneficial uses. To comply with these standards DWR and USBR constructed the initial facilities described earlier, funded monitoring and research in the marsh, and acquired (and set aside) lands to protect listed species such as the salt marsh harvest mouse.

To plan, monitor, and implement the new measures through the 2000 fiscal year, a combination of almost $100 million of DWR, USBR, and State of California General Funds were expended (Table 10). This figure includes some of the major structures (e.g. the SMSCG at more than $20 million) as well as funds to maintain the infrastructure, provide standby pumps for landowners' uses when gravity is not adequate to drain and fill their ponds. Through the late 1980s the funding split was approximately DWR - 40%, USBR - 40%, and General Fund - 20%. (The General Fund contribution was in recognition of the effects of upstream diversions on inflow to and outflow from the Delta (e.g. the City and County of San Francisco, East Bay Municipal Utility District, Modesto and Turlock irrigation districts, riparian diverters, etc.) Since about 1987 there has been no general fund contribution to the marsh program. I must emphasize that the private duck club owners have also spent large amounts of money on their own properties to maintain habitat and hunting opportunities.

Table 9. Abbreviated chronology of significant events related to management of Suisun Marsh

Year	*Event*
1962	The Suisun Resources Conservation District is formed by private landowners to handle administrative, regulatory and technical activities in the marsh.
1970	SWRCB Decision 1379 recognizes wildlife problems in the marsh that are associated with operation of the SWP and CVP.
1970	DWR, DFG, USBR and USFWS sign a memorandum of agreement that was intended to lead to selection of a water supply and management plan that would protect and enhance waterfowl habitat in the marsh.
1974	California Legislature enacts the Suisun Marsh Preservation Act, in part to abate the threat of marsh urbanization and in part to require a plan to protect the marsh.
1975	DFG releases fish and wildlife elements of the Suisun Marsh Plan of Protection.
1976	BCDC submits the Suisun Marsh Plan of Protection to the California Legislature.
1977	California Legislature passes Assembly Bill 1717 which adds the 1974 Suisun Marsh Preservation Act to the Public Resources Code and emphasizes the marsh's importance to wintering waterfowl
1978	The SWRCB adopts D-1485 to set channel water salinity standards for the marsh.
1978	DWR, DFG and SRCD sign an agreement to construct, operate and maintain to partially restore and maintain a brackish Suisun Marsh.
1984	DWR publishes the Suisun Marsh Plan of Protection, including an Environmental Impact Report, which proposes staged implementation of the plan to include monitoring, wetland management plans, physical facilities and supplemental releases of CVP and SWP water.
1985	SWRCB amends D-1485 to extend the compliance dates and locations of criteria and water quality standards.
1987	DWR, DFG, USBR and SRCD sign the Suisun Marsh Preservation Agreement. Some key provisions of this agreement were to: (1) improve wildlife habitat on managed wetlands; (2) define project operations with respect to water supply and its management, including facilities and actions necessary to accomplish water supply objectives; and (3) to recognize that wetland managers in the marsh divert water for wildlife management.
1987	DWR and USBR sign two agreements called for in the Plan of Protection - monitoring and mitigation.
1988	The Suisun Marsh Salinity Control Gates begin operating.
1992	NOAA Fisheries issues the first biological opinion affecting the SWP and CVP operations, including a consideration of operating the salinity control gates to protect emigrating winter Chinook salmon,
1993	DWR, DFG, USBR and SRCD began the process of updating the Suisun Marsh Preservation Agreement - known as Amendment 3.
1993	The USFWS lists the delta smelt as threatened. This listing, and required protection measures, will affect the ability of landowners to divert water from unscreened diversions.
1995	The SWRCB adopted a new Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta (WQCP) to protect the beneficial uses of the estuary.
1995	The Suisun Ecological Work Group formed as a component of the Program of Implementation of the 1995 WQCP.
1995	The SWRCB releases D-1641, which in part releases DWR and the USBR from the responsibility of meeting salinity control values in two western marsh stations and allows more flexibility in meeting some objectives.

Table 10. Annual expenditures by DWR, USBR and the California General Fund to plan, implement, and monitor actions and programs to mitigate for water project impacts in Suisun Marsh.

Year	*Costs ($USD)*
1968	10,571
1969	34,181
1970	23,343
1971	1,042
1972	47
1973	0
1974	0
1975	2,709
1976	32,960
1977	37,475
1978	350,831
1979	3,660,099
1980	5,005,759
1981	2,964,974
1982	2,955,705
1983	2,754,094
1984	2,418,344
1985	2,332,773
1986	6,495,322
1987	13,600,701
1988	7,456,364
1989	2,341,960
1990	3,030,010
1991	6,223,042
1992	2,737,259
1993	2,979,255
1994	3,192,213
1995	2,721,978
1996	3,391,678
1997	3,634,267
1998	5,342,834
1999	8,871,864
2000	2,881,903
Total	97,485,557

In recent years the CALFED Bay-Delta Program has invested a significant amount of funds in Suisun Marsh (Table 11). In general these funds have been directed to studies or efforts to increase the amount of tidal wetlands in the marsh.

Table 11. Projects funded by the CALFED Bay-Delta Program in Suisun Marsh, 1995-2002. (Note the list of projects may not be inclusive.)

Year[a]	*Funding*	*Agency*	*Project*
1995	$450,000[b]	SRCD	Determine which SM diversions should be screened first
1998	$200,000	DFG	Hill Slough West Habitat demonstration project- Phase 1
1998	$1,546,016	UCD	Reintroduction of soft bird's beak into SM
2001	$536,750	DWR	Develop restoration plan for self sustaining tidal marsh along Hill Slough - tasks include topographic surveys and hydrologic evaluation of parcels
2001	$87,000	DFG	Hill Slough West Habitat Demonstration Project-Phase 2
2002	$1,046,000	DFG	Acquire up to 600 acres by fee title or conservation easement of land around Suisun Bay for restoration of self-sustaining tidal marshes. Phase 1 includes surveys, public notification, and stewardship upon ownership
2002	$214,000	SRCD	Update individual ownership adaptive management for private parcels in SM
2002	$271,000	UCD	Distribution and abundance of shrimp, plankton and benthos in SM with the objective of evaluating tidal marshes as a refuge for native species

a. Year approved - not the year the funds may have been available

b. Category III funding.

Historic Perspective on Managing Suisun Marsh -- mid-1990s to Present

The division between the two recent historical periods in marsh management is somewhat arbitrary but is based roughly on some emerging thinking regarding managing Suisun Marsh. From the 1960s through the mid-1990s, the general conceptual model for marsh management centered on the paradigm postulated by DFG in the late 1960s, i.e.:

- The prime purpose of managing Suisun Marsh is to protect waterfowl
- The management occurs mostly on the managed wetlands and tidal wetland development and protection is not a high priority.
- The object in marsh management is to provide water of adequate salinity to promote the growth of alkali bulrush and two other brackish water plants.
- The CVP and SWP diversions will continue to increase over time and will increase salinity in marsh channels, thus requiring extensive physical facilities to provide water of acceptable salinity to private duck clubs and to public wildlife areas.

Although there were modifications to this broad conceptual model - e.g. discontinuing salinity standards in the western marsh and the need to modify maintenance and other operations to avoid jeopardizing at risk species - the basic model continued to hold into the mid-1990s. In recent years, several administrative and physical events have occurred that may result in rethinking the original model somewhat, or at least will require that marsh managers consider fine tuning the model. Following are some of these events we think are important in future marsh planning.

The 1994 Bay-Delta Accord and Water Quality Control Plan. The Accord and WQCP began to address the concept of ecosystem, as opposed to single species management.

The 1998 Levee Breaks in Suisun Marsh. In February 1998 a combination of high tides, low barometric pressure, high winds and ocean conditions combined to breach or overtop Suisun Marsh levees at 60 locations. Levees along Grizzly and Honker bays and the lower Sacramento River had 11 major breaches of approximately 100 feet each. As a result of the levee breaches, about 22,000 acres of 57,000 acres of managed wetlands were flooded. DWR and the USBR funding repair of the 11 exterior breaches at a cost of more than $1 million.

Following the 1998 levee breaks in Suisun marsh, a Suisun Marsh Levee Investigation Team was assembled at the request of the CALFED Policy Group to conduct modeling analysis, ecosystem restoration research, and public outreach in order to determine whether including a Suisun Marsh levees component in the Levee Program would contribute to the overall objectives of the CALFED Program in a cost-effective manner. An important outcome of that investigation are the results of modeling that was used to examine the effects of these and other possible breaches on water quality in the northern bays and the Delta (see for example, Enright et al. 1998). The modeling indicated the number, size and location of breaches in exterior Suisun Marsh levees had the potential to affect water quality in the Delta, and thus the quality of water exported from the Delta. The modeling results showed dramatically that what happened in the marsh had wider implications to the estuary. The 1998 flooding and resulting modeling work lead to a recommendation that protecting Suisun Marsh levees be included in the CALFED Bay-Delta Program's Levee System Integrity Program (CALFED 2000).

The 1999 Baylands Ecosystem Habitat Goals Project Report (Goals Project 1999) . The Goals Project began in 1995 with the following purpose statement:

> *The San Francisco Bay Area Wetlands Goals Project will use available scientific knowledge to identify the types, amounts, and distribution of wetlands and related habitat needed to sustain diverse and healthy communities of fish and wildlife resources in the San Francisco Bay Area. The Project will provide a biological basis to guide a regional wetlands planning process for public and private interests seeking to preserve, enhance, and restore the ecological integrity of wetland communities.*

The 1999 Goals Project report specifically called for retention of managed wetlands in Suisun Marsh (with "enhanced" management practices to increase their ability to support waterfowl) and restoration of tidal marshes along the marsh's periphery - i.e. along Suisun, Grizzly and Honker bays. For the first time, restoration of tidal wetlands in Suisun Marsh was identified as an important ecosystem objective.

The 2000 CALFED Record of Decision and Ecosystem Restoration Plan. CALFED called for the restoration of 5,000 to 7,000 acres of land in Suisun Marsh to tidal wetlands. The program would achieve the restoration goal through a cooperative program that resulted in fee title or conservation easements. The restoration of tidal wetlands would be conducted as part of an overall marsh management plan that recognized the importance of managed wetlands to wildlife protection.

The 2001 Suisun Ecological Workgroup (SEW) Final Report. After about six years of work SEW submitted its final report to the SWRCB (IEP 2001). Although the various subcommittees (Brackish Marsh Vegetation, Waterfowl, Aquatic Habitat, and Wildlife) could not reach complete agreement on all recommendations, SEW represented one of the most comprehensive examinations of marsh ecology and management needs since intensive marsh management began in the 1960s. The reports analyses and recommendations provide a useful reference for future marsh planning and research.

The CALFED Charter. During an impasse among the agencies working on an amendments to the Suisun Marsh Preservation Agreement (SMPA) and renewal of the SRCD Regional General Permit from the USACE, the agencies were requested to develop a charter to address these issues as well implementation of the CALFED program in Suisun Marsh.

The goal of the CALFED Charter is to develop a regional plan that balances implementation of the CALFED Program, SMPA, and other management and restoration programs within Suisun Marsh, in a manner responsive to the concerns of stakeholders and based on voluntary participation by private landowners.

The following agencies are key members of the Charter process:

- NOAA Fisheries
- US Army Corps of Engineers
- USBR
- USFWS
- DFG
- DWR
- SRCD
- California Bay-Delta Authority

The CALFED Charter continues the movement towards an ecosystem approach to managing Suisun Marsh, as opposed to a focus on waterfowl and single species management.

In his presentation Pacheco indicated that the initial Charter process had developed a draft Suisun Marsh Implementation Plan, but there was disagreement on environmental documentation needs to implement the plan and move forward. In June 2003, the agencies re-initiated the Charter process to develop a Habitat Management, Restoration, and Protection Plan for Suisun Marsh. Scoping meetings were held last fall to present the goals and issues for review and input.

Through this public process, the agencies and stakeholders have developed a list of goals and issues for habitat management, preservation, and restoration of Suisun Marsh. The goals and issues identified thus far relate to:

- Ecological Processes
- Habitats
- Levee system integrity
- Non-native invasive species
- Water and sediment quality
- Public use and waterfowl hunting

Each of the goals and issues has been further sub-divided, for example, the category of ecological processes has the following sub-categories.

- Rehabilitate natural processes
- Support aquatic and terrestrial biotic communities and habitat
- Favor native species
- Focus on waterfowl and sensitive species

The goals and issues are intended to foster discussion, analysis and planning that will result in a plan that accomplishes the overall Charter goal shown above. The Charter group has charged a subset of the overall group to develop conceptual models of how many of the biologic and physical systems work in the marsh. As with all conceptual modeling, the objective is to get the models on paper to help identify areas where the knowledge base is solid, where it is not, and, critical areas needing more data collection and/or analysis.

One goal of the Charter agencies was for this workshop to identify knowledge gaps that have potential for inter-disciplinary science and promote collaboration in the marsh. The workshop would also assist the Charter Group with efforts to integrate scientific knowledge into the Development of the Suisun Marsh Plan.

Managing Suisun Marsh's Diked Wetlands

Steve Chappell of the SRCD described how the landowners manage their properties to:

- Provide wintering waterfowl habitat
- Provide habitat for resident breeding waterfowl and ground nesting birds
  - Upland nesting habitat
  - Permanent ponds and brood rearing habitat
- Sustain hunting opportunities and experience
- Maintain and enhance wetland conditions for resident and migratory species
- Protect open space and wetlands habitat from development through habitat stewardship

Chappell emphasized that physical, environmental, regulatory, and fiscal constraints affect the ways in which diked wetlands are managed.

Physical Constraints

Physical constraints generally involve the ability to move water on and off the clubs and the differing soil characteristics on the individual clubs. Wetland elevations, pond topography, and water control infrastructure are keys to successful water control and management. Soil subsidence can affect the ability of individual water diversions and drains to flood and drain the ponds on the desired schedule. The fish screens on screened diversions must be periodically maintained to ensure that they remain workable to prevent head-loss clogging by algal growth, debris, etc. does not occur across the screen face.

Environmental Constraints

The environmental constraints are tied to the location of individual clubs within the marsh and annual, seasonal and tidal variation of the stage and quality of water available at individual water intakes. For example, clubs on the west side of the marsh experience different salinity conditions than do clubs on the east.

Regulatory Constraints

Regulatory constraints now pose one of the largest challenges in managing diked wetlands in Suisun Marsh. Among the most important of these constraints are:

- Compliance with provisions of the 1977 Suisun Marsh Preservation Act
- Various provisions of the USACE permitting system including Section 401 water quality certification, section 404 of the Clean Water Act, and section 10 of the Rivers and Harbors Act.
- Endangered Species Act compliance that seasonally limits diversions through unscreened intakes to protect listed fish species. The state and federal ESAs also limit the periods during which levee maintenance work can be accomplished.
- Air quality standards limit the periods during which marsh vegetation can be burned.
- The Solano Mosquito Abatement District may require club managers to delay flooding to limit mosquito-related concerns. Typically this means that flooding may not begin before October 1.

Fiscal Constraints

Finding the money for club management and maintenance of facilities and infrastructure are often a problem. Funding of wetland restoration and enhancement projects through cost-share grants has historically been a very effective way of improving habitat and encourage partnerships with public and private interests.

Figure 49 is a draft conceptual model of the existing management cycle on Suisun Marsh's diked wetlands, including periods where regulatory constraints limit maintenance and club management activities. Most of the clubs use several variations on the flooding cycle but the most typical are the long and short hydroperiods - with the differences being ponds flooded for more than 6 months in the long hydroperiod and less than 6 months for the short. Figure 50 shows a typical long hyroperiod water management schedule. The schedule is designed to provide habitat for wintering birds, hunting opportunities, leaching to reduce salt concentration in the soil profile and optimum conditions for seed set and germination. As shown in the general diagram in Figure 51, the different hydroperiods result in different vegetative pattern in the wetlands.

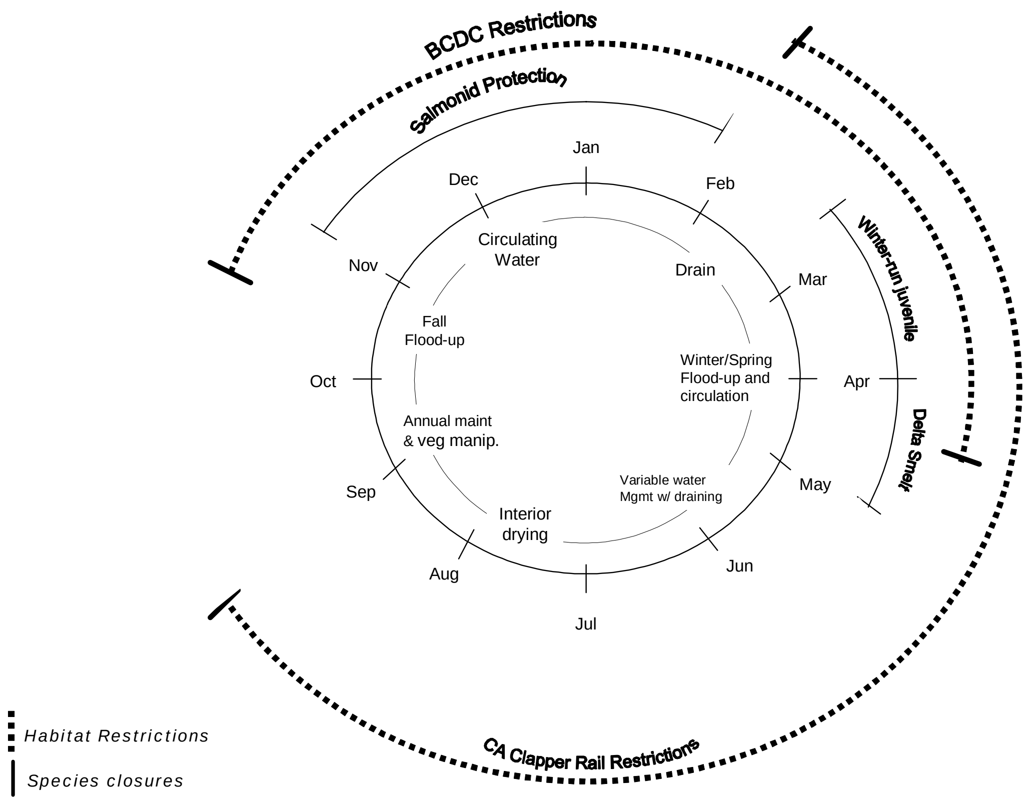


Figure 49. Draft conceptual model of existing Suisun Marsh managed wetlands management cycle. (Source: S. Chappell.)

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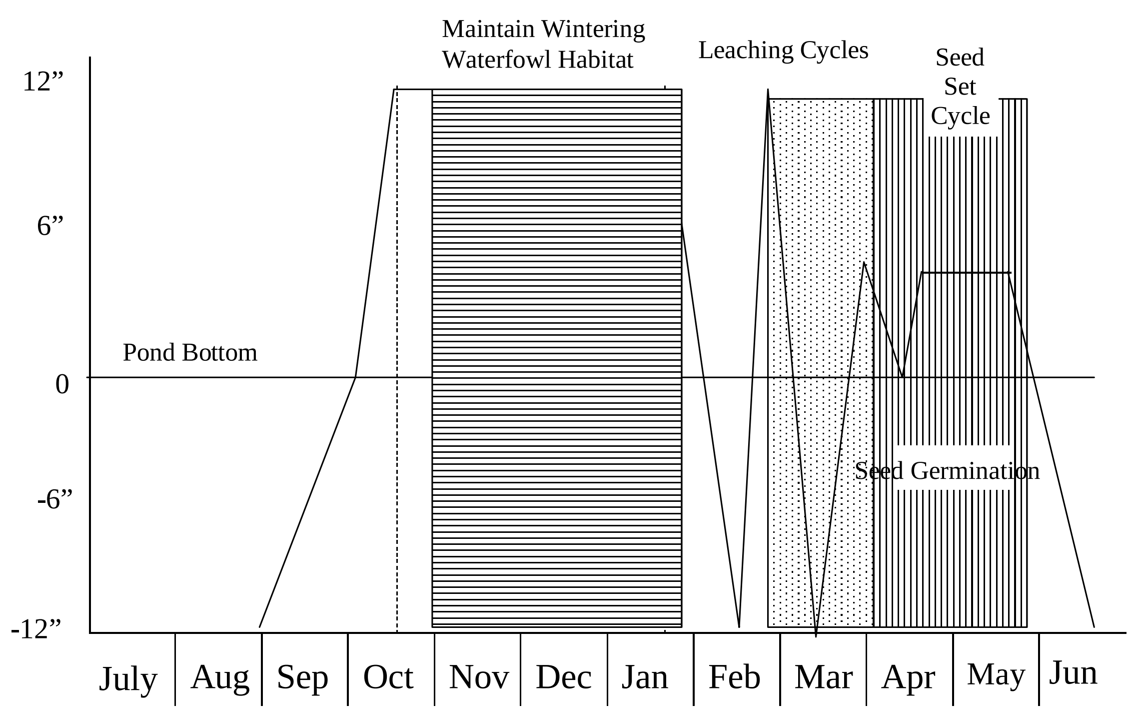

Figure 50. Long hydroperiod water management schedule. (Source: S. Chappell.)

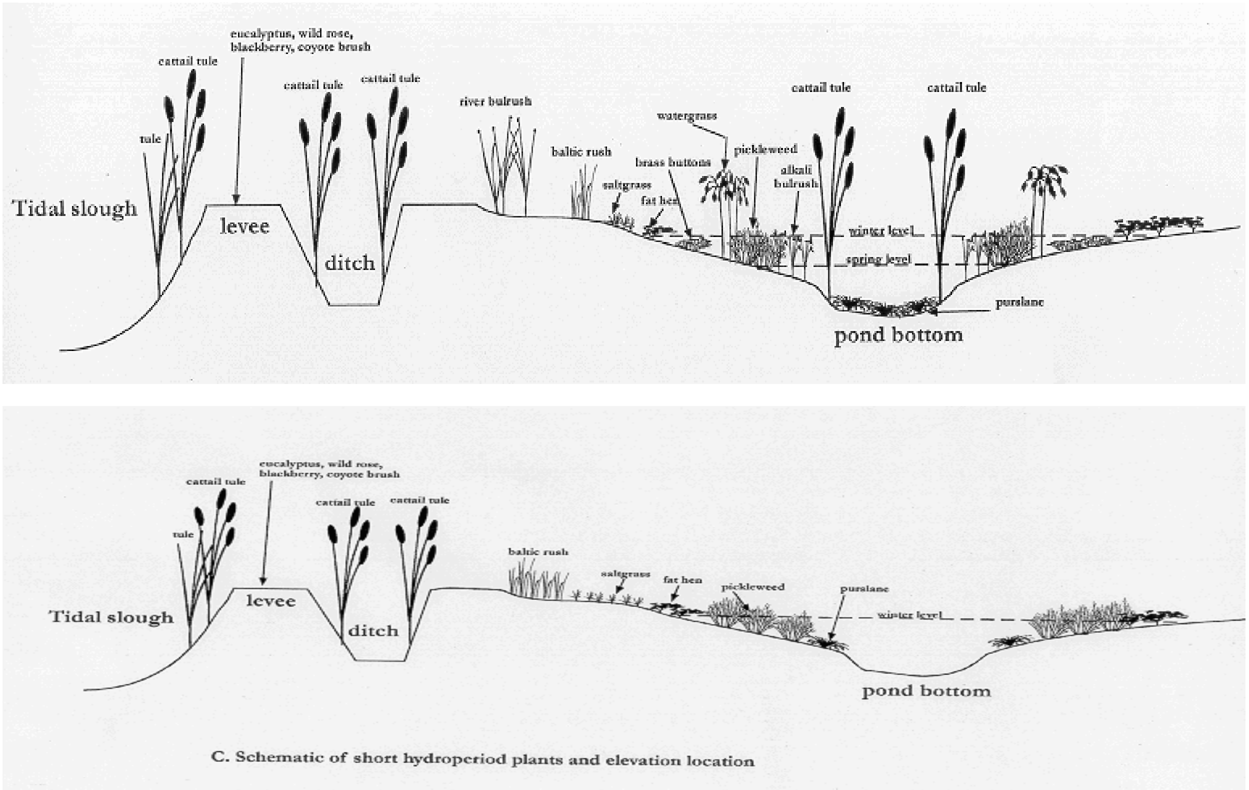

Figure 51. Plant communities resulting from long and short hydroperiod management. (Source: S. Chappell.)

Chappell noted that efficient and effective wetland management is dependent on maintenance of levees, water control structures, and water conveyance facilities. New corrosion resistant materials are being developed for use in the marsh, but cleaning of ditches, coring interior levees and replacement of leaking water control structures will always be required.

To get beyond management to enhancement, Chappell presented the conceptual model shown in Figure 52. He emphasized that additional study is needed in the following areas to refine management and enhancement strategies.

- Wetland values and functions
- Use of the marsh by Endangered Species Act listed species that will result in better species protection and more effective wetland management
- Waterfowl food plant production and availability
- Ecosystem and waterfowl values of managed wetland versus those in tidal wetlands and restored tidal wetlands
- The relationships among soil chemistry, leaching, and acid sulfate soil reactions

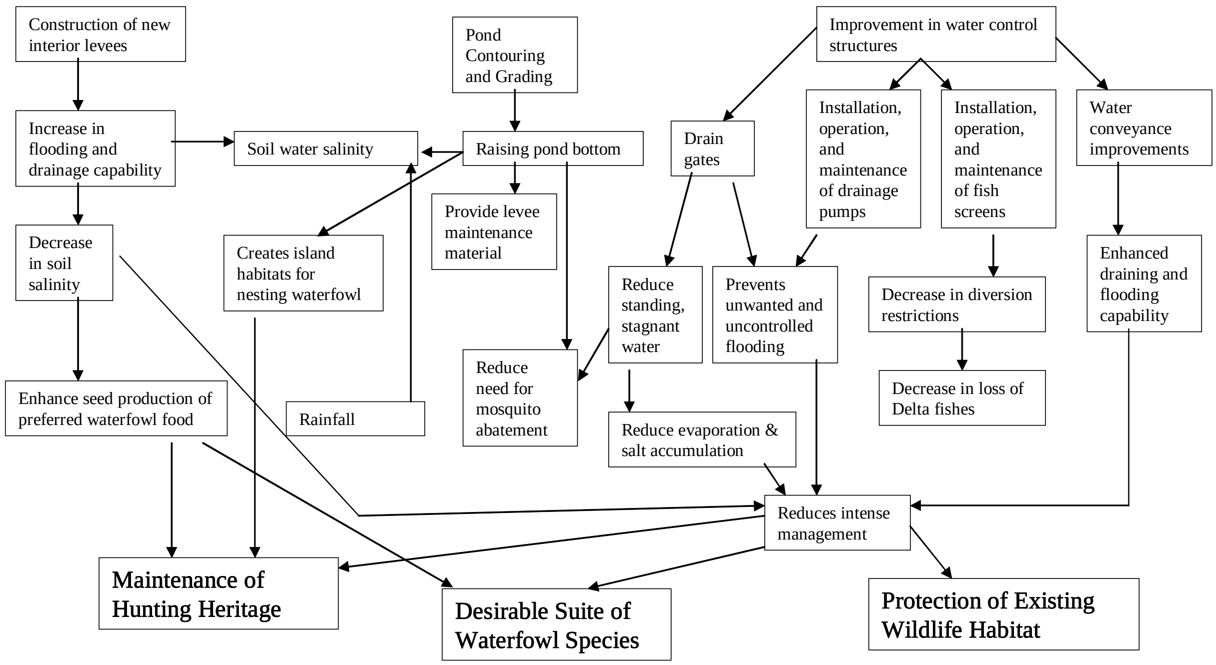

Figure 52. Conceptual model of managed seasonal wetlands enhancement. (Source: S. Chappell.)

Conceptual Models in Suisun Marsh

Conceptual models, their purpose and use, were integral components of many workshop presentations. As Hymanson pointed out early in the workshop, conceptual models are essential science tools in that they explicitly lay out how we think things work. Almost everyone working in the marsh and the estuary has a conceptual model, but until recently most of them had not been committed to paper. The models may be very simple - e.g. more flow means more fish - or they may be quite complex with pages filled with boxes and arrows. In most cases the simple and complex models have one common characteristic - they are driven by assumptions. One of the benefits of the models themselves is that they help identify the key assumptions and point to the need to obtain data needed to move from assumption to more solid scientific ground. As we increase the accuracy and reliability of our conceptual models we often find that some of early assumptions based on “conventional wisdom” or intuition were leading us astray. Conceptual models can lead to more mechanistic (and predictive) models and are an essential first step when thinking about, and developing a science agenda for an area such as Suisun Marsh. Perhaps more pragmatically conceptual models are required component in applications for grant and other science funding from the CBDA.

Many of the presentations included conceptual models. In addition, Peter Moyle and his colleagues and Chris Enright and Steve Culberson submitted several models specifically in response to a request from the workshop planners. Some of these models were shown on the second day of the workshop, followed by a brief discussion. Due to space limitations, we are only showing four of these models in this section. The models selected are simply to show the variety of ways in which models can be constructed - not that these models are the most correct statement of our understanding of the processes. One of the goals of conceptual models is to stimulate discussion and that is certainly the case here. Inclusion of a model, or the amount of space devoted to a particular model has no particular relation to its validity or to our support for it.

I start with a model of organic carbon cycling in Suisun Marsh submitted by Anke Mueller-Solger (Figure 53). This model is very preliminary and general but dramatically illustrates the complexity of the real world situation. A four page explanation of the symbols in the model, Appendix C), identifies the natural and anthropogenic factors that influence the sources and fate of the organic carbon - not only in the marsh but in larger estuarine system. The model clearly shows that we must not consider the marsh as an isolated feature of the estuary but as an integral component. The model and the text in the attachment provide a useful framework to consider when contemplating the design of a science agenda for the marsh and the estuary.

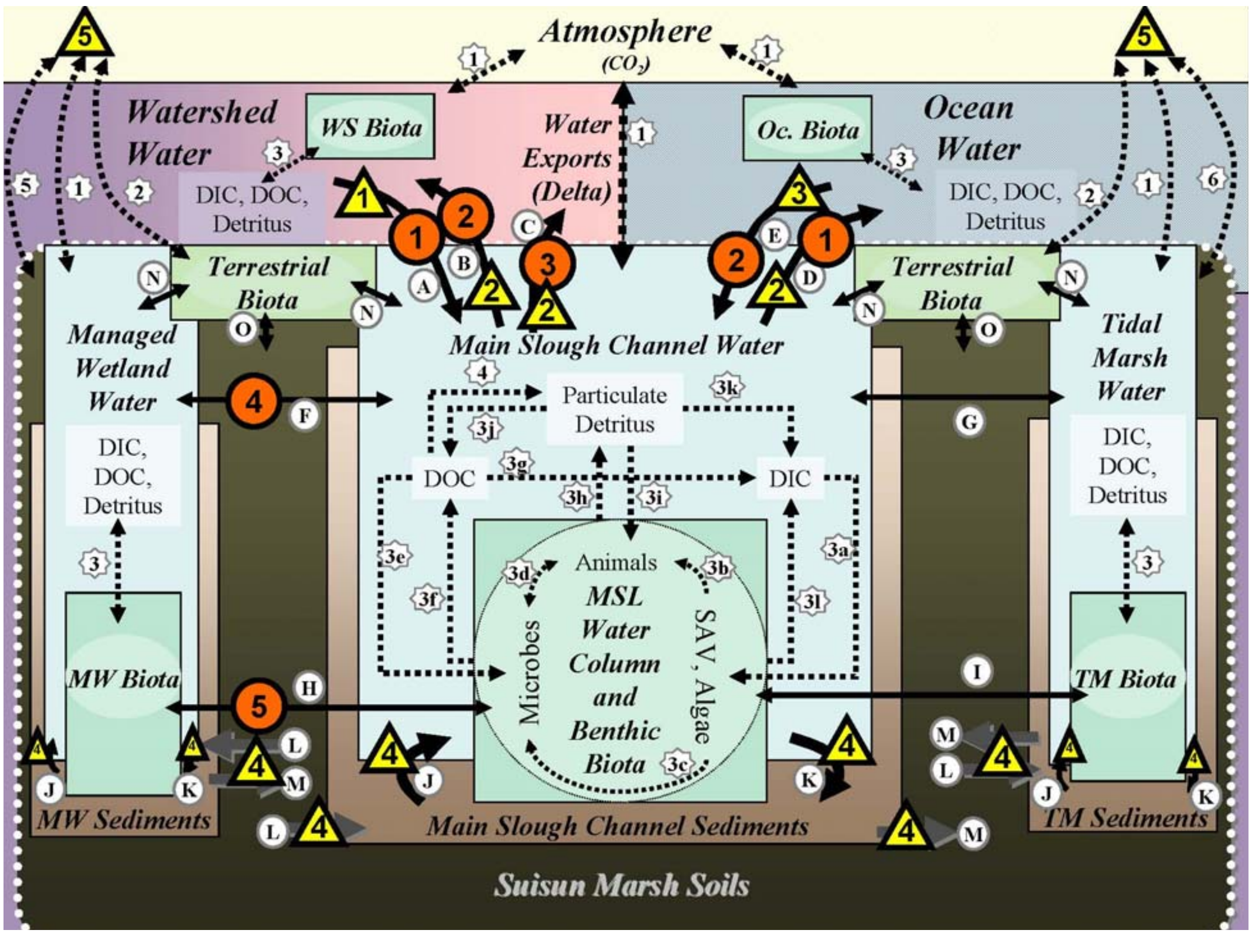

Figure 53. Conceptual model of carbon movement in Suisun Marsh. (Source: A. Mueller-Solger.)

The second conceptual model to be considered, by Steve Culberson, also involves carbon (Figure 54) but in a more specific sense of its role in maintaining or increasing soil surface elevations in the marsh. A sub-element of the model (Figure 55) illustrates the way in which Culberson visualizes soil formation in the marsh and the critical role vegetation plays in this process. This model and its ramifications should be considered when thinking about creating tidal wetlands in the marsh and the effects of current management practices on soil subsidence.

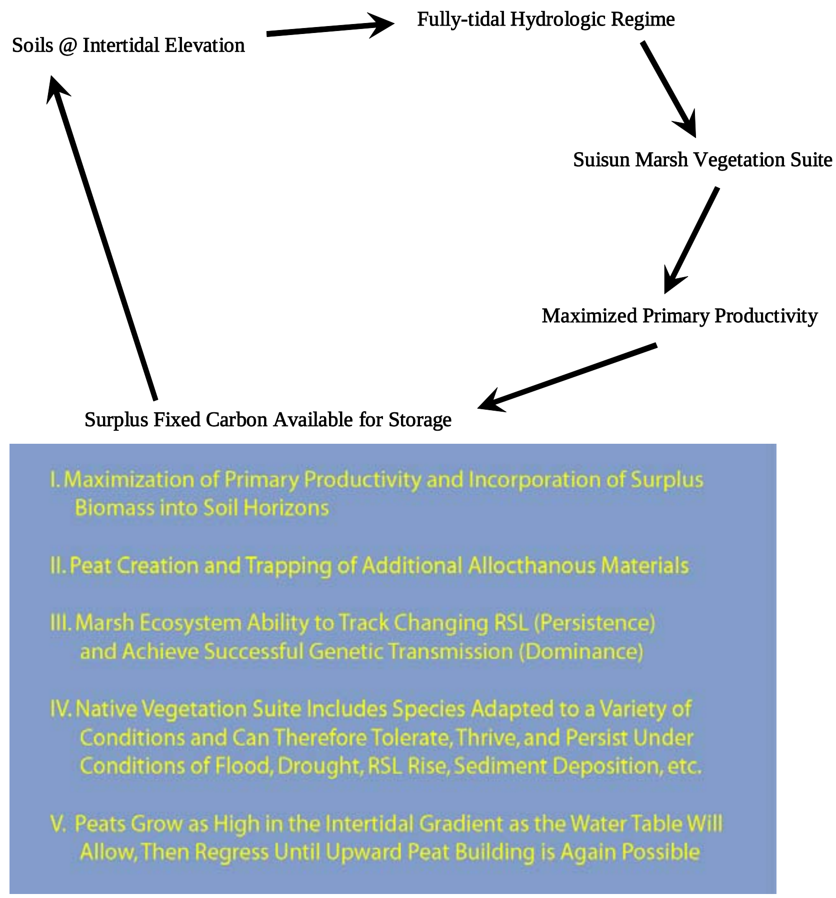

Figure 54. Conceptual model of Suisun Marsh as a carbon storage vessel. (Source: S. Culberson.)

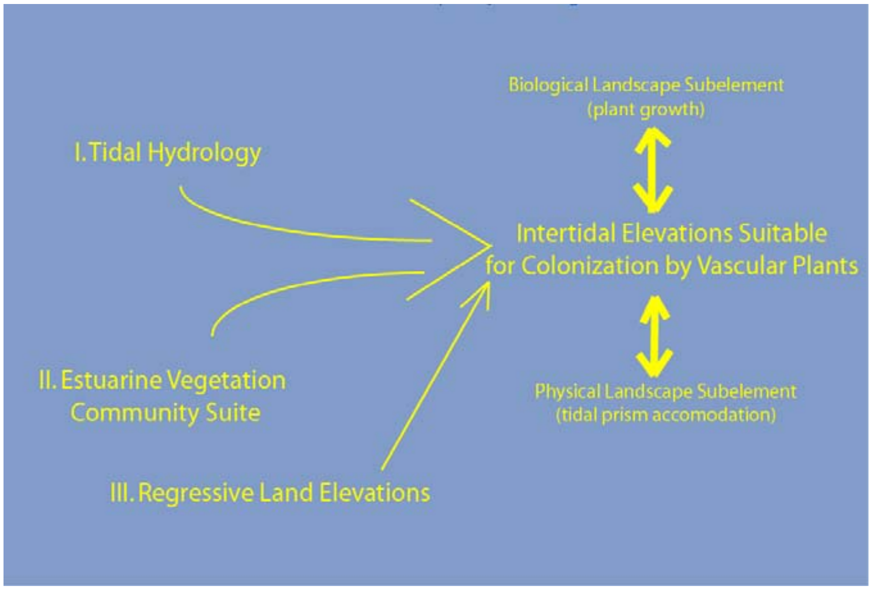

Figure 55. Conceptual model of Suisun Marsh geomorphology. (Source: S. Culberson.)

The third conceptual model, from Chris Enright, uses the narrative format rather than boxes and arrows to examine the relation between channel water salinity and waterfowl productivity - i.e. the conceptual model underlying Suisun Marsh management. This is an abbreviated version of the model - the complete model and a model on marsh soils are found in attachment 4 In spite of its length, I have included an slightly edited version of the model because I believe it raises some important points that emphasizes, the possible changes in the Suisun Marsh conceptual paradigm that must be considered in future marsh management scenarios. It is also included because Enright not only proposes a conceptual model but looks at how it holds up with available data.

Conceptual Model of Channel Water Salinity and Waterfowl Productivity by Chris Enright

The premise behind water project involvement in the Suisun Marsh is that reduced Delta outflow due to project exports increases the salinity of the marsh and ultimately reduces waterfowl productivity. Analog estuarine salinity field modeling in the early 1960s by DWR reported in Mall (1969) predicted that, with water project build-out, the annual average salinity in Suisun Bay would approximately triple by 1990. As of 2004, the SWP has achieved about 60-70 percent of the original plan “build-out.” Mall built upon prior work by George et al.(1965) who identified the primary food plants used by dabbling ducks in the marsh. Mall’s paper reported the influence of seasonal soil salinity on waterfowl food plant productivity. A third paper by Rollins (1973) reported the influence of channel water salinity on soil root zone salinity and suggests soil salinity control management strategies. These papers are the basis of seasonal salinity standards set for the Suisun Marsh to protect waterfowl. Alkali bulrush (*Scirpus maritimus*) is identified as the primary food and indicator plant species. Salinity standards set by the SWRCB (1995) are intended to achieve 90 percent of maximum alkali bulrush seed production and 60 percent seed germination.

The complete mechanistic link between water project operations and waterfowl productivity has not been made despite the historical presumption, programmatic effort, and provision of large salinity control facilities since Mall’s 1969 paper. The bare-bones conceptual model that would make this linkage is represented thusly:

Reduced outflow caused by water projects in turn affects:

- estuary salinity
- applied water salinity
- soil water salinity/soil biogeochemistry
- plant productivity and assemblage
- waterfowl abundance

Enright goes on to look at the components of his conceptual model.

Estuary Salinity

An analysis of historical salinity in the Suisun Marsh and Suisun Bay is being conducted by Enright and Harrison (in prep.) and was discussed earlier. Salinity data were compiled for Port Chicago (since 1947), Beldons Landing (since 1929), and Collinsville (since 1921) from the DWR Bulletin 132 series. These analyses show that, while Delta outflow decreased an average of 22 percent compared to what it would have been without the water projects, small watershed precipitation trend increases may have largely compensated. Fox et al. (1990) first identified this effect. Using an estuary model, Knowles (2001) showed that Suisun Bay salinity has increased from an annual average of about 6 ppt to 7ppt due to combined reservoir and export operations. Enright and Harrison (2004, in prep.) further showed that salinity variability from the tidal to the decadal time scale is much larger than variance in the trend, and that there are other influences on the estuary salinity regime trend including the approximately 1 meter deepening of Suisun Bay since 1922.

Despite the intra-annual variability reducing effect of the water projects (reducing outflow in spring, increasing outflow in summer and fall), post-project salinity variability has been greater than pre-project salinity variability. There was little indication of long-term salinity trend in Suisun Marsh and Suisun Bay.

Applied Water Salinity

Suisun Marsh managed wetlands conduct water operations by gravity flow for the most part. The salinity of applied water is therefore biased toward mean to high tide salinity since the larger head differences drive more water volume on to managed lands. Aside from notable exceptions, high tide and lagged flood currents are of significantly higher salinity than end of ebb currents near low tide. During warm months, this applied water therefore has a higher mean salinity than channel water and is subject to concentration by evaporation. Resultant root zone salinity is significantly higher than applied water salinity.

Soil Water Salinity and Soil Biogeochemistry

This link in the mechanistic chain connecting water project operations to waterfowl abundance is the most uncertain and ripe for research. Process understanding of contaminant, carbon, and nutrient cycling are in their infancy and require investment in long-term research. In letters to the Suisun Resource Conservation District Board and SEW Wildlife committee, long-time Suisun Marsh manager Paul Crappuchettes (1999) recounts 30 years of observations and management experiments that focus primarily on "acid sulfate syndrome" that afflicts otherwise properly managed areas and that are unrelated to channel water salinity. He describes the acid sulfate production process and its correlation with soil drying, soil temperature, disking, and burning. He makes specific recommendations about water control on managed wetlands depending on salinity, water control facilities, and pond elevations including rapid circulation of pond water to maintain alkalinity. Lands that cannot circulate at a high rate because of subsided elevations should be permanently flooded during the growing season with maximum possible circulation. He suggests that marsh soils require at least seven years to achieve equilibrium response to management changes. He ultimately recommends collaboration with university researchers and the Soil Conservation Service to provide the science basis for waterfowl based wetland management plans.

Another seasonal feature of managed wetlands is "black water" caused by oxygen deficient organic material decomposition by sulfate reducing bacteria. Excretions include carbon dioxide and hydrogen sulfide that reacts with iron in the soil to produce iron sulfide, which is black. Soil salinity is likely a mediating chemical factor in this process but water management is usually cited as the key controlling factor (Rollins1973). The monthly UC Davis fish monitoring program has measured dissolved oxygen since 1999 (Robert Schroeter, UCD, pers. comm.). They have found a pattern of depressed DO in the fall and often in the spring that is thought to be directly related to seasonal wetland drainage.

These issues represent only two among many soil biogeochemistry issues that affect plant productivity and contaminants cycling. They have two characteristics in common: they are poorly understood and ripe for research to uncover process mechanisms that could improve management, and there appears to be limited role of channel water salinity in the processes.

Plant Productivity and Assemblage

The primary reference for plant productivity related to soil salinity is from Mall (1969). The relationship between alkali bulrush seed yield and monthly soil salinity was determined. Mall concludes that May salinity is critical to September seed yield, and optimal May soil salinity is between 7 and 14 ppt. Channel water salinity of 6 to 8 ppt would provide this level of soil salinity. Figure 56 shows that Beldons Landing salinity has been below 8 ppt 100% of the time since 1929. If Port Chicago can be considered a surrogate for western Suisun Marsh salinity regime, optimal May alkali bulrush salinity was available as applied water approximately 75% of the years, which includes the 1987-1992 drought. Aside from this optimal range, Mall (1969) found that alkali bulrush was found in dominant stands with root zone salinity above 30 ppt.

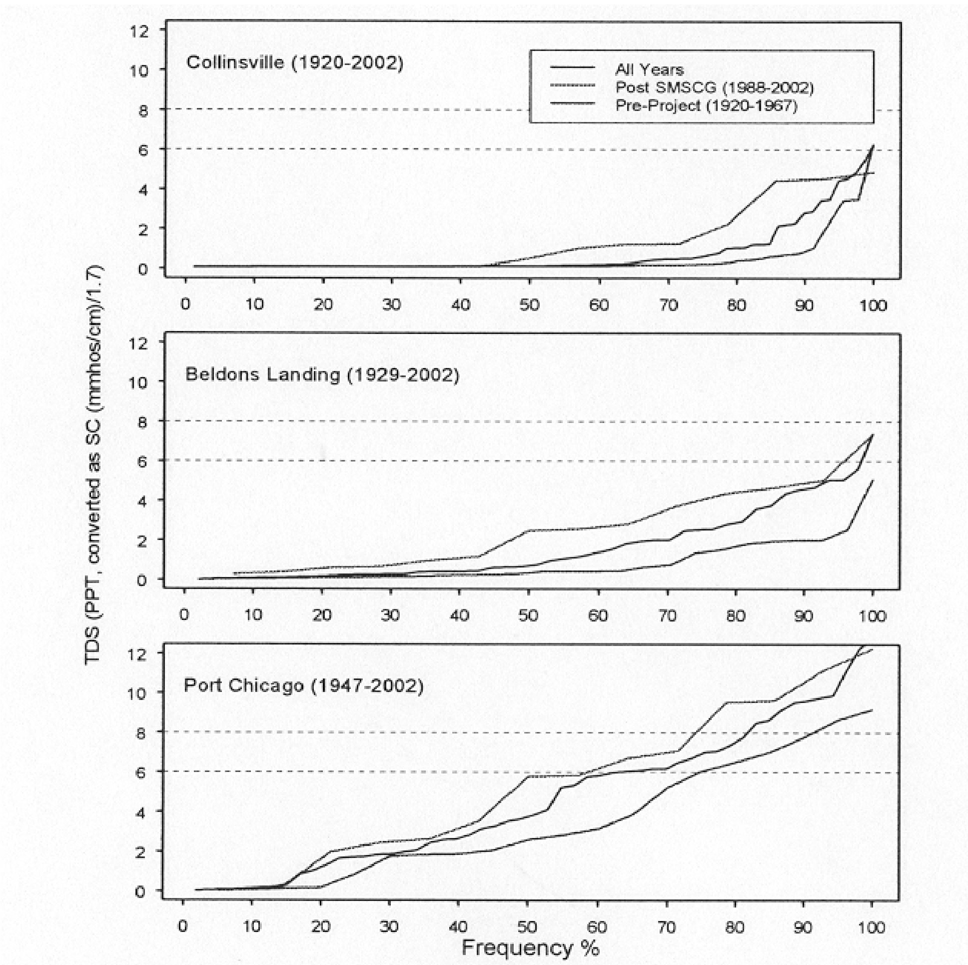

Figure 56. Frequency of average May applied water TDS. Black line represents average May TDS for the period of record shown; blue line is post SMSCG period beginning in 1988; red line is the pre-water project period up to 1967. Horizontal lines (6-8 ppt) represent the "optimal" applied water salinity to achieve optimal soil water salinity of 7-14% according to Mall, 1969. (Source: C. Enright.)

Length of soil submergence is the most important factor influencing plant distribution and competitive ability. Within tolerances for submergence, root zone salinity ranked second behind water management in determining presence or absence of a given species.

The historical assumption that water project operations have increased salinity far above presumed food plant tolerances is shown by the data to not hold. Moreover, water management is most often cited as the key factor determining plant productivity and assemblage. Therefore, the assumption that channel water salinity is the primary determinant of plant productivity is incomplete at best. Accepted principles of plant ecology consider that productivity depends on many other factors including hydroperiod (controlled by management), nutrient status, soil redox potential, soil type, disturbance factors, herbivory, dispersal, and interspecies competition and facilitation. For the current conceptual model to be useful, it must explain the linkage between these physical, chemical, and biological factors and applied water salinity.

Waterfowl Abundance

Dabbling ducks in the Suisun Marsh are all known to use brackish water habitats well down into the San Francisco Bay. The primary salinity related concern for waterfowl is use of the marsh as waterfowl brood habitat in the spring. Mallards require relatively fresh water habitat in the first few weeks of life. Mallard brood habitat in the marsh has apparently become an important contribution to the Pacific Flyway population (Suisun Marsh 2004 workshop presentation by Mark Petrie of Ducks Unlimited). Long-term salinity trends for May and June at Beldons Landing and Port Chicago suggest that salinity has increased about between 2 and 4 mmhos/cm since 1929 and 1947 respectively. It is an open question for research as to if this increase has a brood productivity impact compared to other sources of pond salinity variability like concentrated soil salinity leaching into brood water.

Overall it appears that salinity is an important physical/chemical factor for waterfowl abundance and productivity. However, it is one factor among many for marsh geochemistry and food web biology. It may be that the prevailing conceptual model that links water project operations to waterfowl productivity may be in need of revision and persists simply by historical inertia. Salinity trend analysis does not show the expected magnitude of Suisun Marsh salinity increase that was forecast in the 1960s. Salinity variability across time scales from tidal to decadal have more variability than the trend. Even if salinity trends were shown to be significant, a clear mechanistic description of how applied water affects soil biogeochemistry, plant productivity, and ultimately, waterfowl abundance appears tenuous and has otherwise not been advanced.

Model of Circulation and Inputs in Suisun Marsh by Peter Moyle

For the last conceptual model, we return to boxes and arrows in model from Peter Moyle of circulation and inputs to the marsh, Figure 57. The following explanatory text for Figure 57 is directly from Moyle.

This is a general model of sources of water, nutrients, and aquatic organisms for Suisun Marsh, reflecting its connections with the surrounding region.

A. The main source of freshwater input is the Sacramento River, with the amount varying with season and year (generally, high freshwater inputs in winter/spring, low inputs in summer/fall). The tidal gates at the mouth of Montezuma Slough regulate marsh circulation during periods of low freshwater inflow. The inflowing water enters through Montezuma Slough which is the main artery delivering water to most of the marsh, through other large sloughs (mainly Suisun Slough). Two of the most important fishes of the marsh, striped bass and splittail, spawn in upstream areas during the spring and the river delivers juvenile fish to marsh for rearing. Juvenile Chinook salmon also come in via this route.

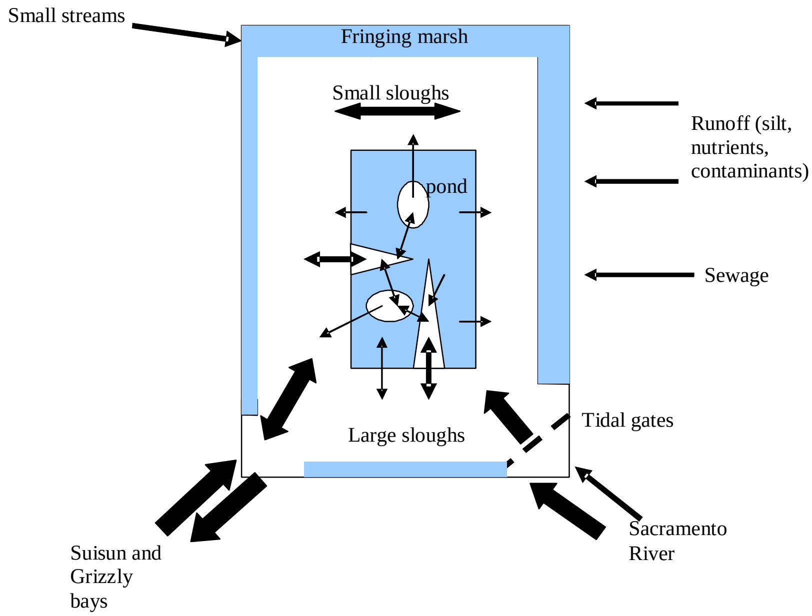

Figure 57. Conceptual model of Suisun Marsh ecosystem - circulation and aquatic inputs.

B. At the southwestern end of Suisun Marsh, water from Suisun Bay enters Montezuma and Suisun sloughs through strong tidal action, moving back and forth on a daily basis with the tides, although the tidal action is modified by the amount of inflowing fresh water and by the tidal gates. This tidal action results in large numbers of fish and invertebrates moving in and out of the marsh. Larvae and juveniles of brackish water species (e.g. starry flounder, staghorn sculpin) enter the marsh for rearing and leave later in the year, usually as the marsh become fresher. Fish moving through the Montezuma Slough leave by this route.

C. The freshwater streams (e.g., Suisun, Green Valley, Denverton creeks) that flow into the marsh provide an additional source of freshwater, especially in the spring. They are presumably the major spawning areas for some fishes (e.g., Sacramento sucker) and may create flooded areas that are used by spawning for other fishes (e.g., common carp).

D. Suisun Marsh is surrounded by urban development and transportation corridors. These are sources of run-off in winter that presumably contain contaminants of various sorts, although the amount and impact of these contaminants is not known.

E. Tertiary treated sewage from Fairfield and Suisun City is poured into the marsh for final treatment. This is a source, year around, of fresh water and nutrients. The facility is proposed for expansion, so its effects on the marsh are likely to increase. The effects of this discharge on the marsh ecosystem are not known.

F. There are numerous small sloughs in the marsh with complex circulation patterns and strong tidal influences. Most have been dredged and leveed in the past but those that have not seem to have the richest native fish and invertebrate fauna.

G. Much of the marsh interior is separated from the tidal sloughs by gates and dikes. The interior is intensely managed as brackish-water marsh for waterfowl, although it contains many permanent water bodies as well (isolated sloughs, ponds, etc.). Some sloughs are used as systems to deliver water to duck clubs, the largest being Roaring River Slough. Water used to seasonally flood duck clubs often spills over into tidal sloughs or is drained into them, and can have a major impact on water quality, resulting in fish kills. Although the sloughs and the interior marsh are usually treated as separate entities, they clearly have multiple and complex connections.

Suisun Marsh Restoration

Before I describe the restoration talks given at the 2004 Suisun Marsh workshop, it might be helpful to briefly discuss the concept of restoration itself. The first question folks often ask (and should ask) when hearing about restoration proposals, is "To what time period are you trying to restore?" In no case is it possible to go back to pre-gold rush conditions. Because of this fact, what is the "basis" for restoration? Restoration ecologists may answer the question as follows: restoration should restore lands in the context of the suite of physical, chemical, and biological processes now acting on the land to be restored, Natural analogues help define what the outcome may be following sufficient time the restored marsh to evolve. Unfortunately Suisun Marsh is comparatively lacking in representative natural analogues, i.e. there is relatively little remnant tidal marsh habitat.

In any event, when discussing restoration, it is critical that the restoration target be clearly identified early on in the process. In many cases, the term "re-creation" should be substituted for "restoration," and even re-creation does not capture the complexity of the process in that re-creation and restoration science are in their infancy. Moving dirt and encouraging plant communities does not always yield the intended results - for example exotic species may colonize the area: not the native species that were to be the intended project beneficiaries.

In the case of Suisun Marsh, the restoration target is to establish more tidal marsh - but not to recreate the amount of tidal marsh found in any at any particular time in history. The most immediate target is the 5,000 to 7,000 acres of new tidal marsh identified in the 2000 CALFED Programmatic Record of Decision. Tidal marsh restoration at this level is intended to support a more natural system, and ecosystem processes, that will yield greater habitat complexity and diversity and will assist in the recovery of at risk plant and animals. An adaptive process is needed to establish the restoration process in such a way that it is amenable to monitoring, analysis, tweaking as called for, and identifying appropriate performance measures against which success can be judged. The now underway Integrated Regional Wetlands Monitoring Program (Siegel et al 2002; Bollens et al. 2002) might serve as a useful model for the scientific (research and monitoring) aspects of proposed restoration projects in Suisun Marsh and elsewhere.

Tidal Marsh Restoration in Suisun Marsh

General Principles. Stuart Siegel, working with CALFED, led off the restoration presentations with a discussion of the challenges and opportunities involved in restoring tidal marshes in Suisun Marsh. Siegel emphasized that "We are 're-creating' tidal marsh under modern conditions and constraints on lands where it once existed; we are not 'restoring' the exact marshes of 1850 and before."

To get everyone using the same terms, Siegel defined a tidal marsh as:

- Land inundated daily by the tides, consisting of vegetated marsh plains, channel networks, and at times with ponds and/or pannes;
- Established as islands or adjacent to upland;
- A physiographic template with the geomorphology and the vegetation defining available habitats at macro- and micro-scales; and
- Containing extensive physical and biological linkages.

Although the 2000 CALFED ROD called for 5,000 to 7,000 acres of new tidal wetland habitat in Suisun Marsh, and the Baylands Ecosystem Habitat Goals Report had a goal of 17,000 to 22,000 acres, as of March 2004, zero acres had been constructed. There are about 2,000 acres of new tidal marsh being constructed, or in final planning, in Suisun Marsh - Montezuma Wetlands Project (private, ~1800 acres); Hill Slough (DFG, ~220 acres); and Blacklock (DWR, 70 acres).

Tidal marshes may form either at fast or slow paces - when re-creating marshes we hope that formation will be at the fast pace but there is no guarantee. A conceptual model of tidal marsh formation includes three external controls - salinity gradient, tidal range gradients, and sediment supply. Sediment supply:

- Is vital to marsh growth and maintenance, especially with sea level rise
- Has large spatial and temporal variability due to:
  - – Highly seasonal river and local stream discharge
  - – Proximity to Delta outflow as major sediment source
  - – Proximity to mudflats for re-suspension
  - – Distance to sediment sources and loss en route
- Has large magnitude, infrequent events that can play a significant role especially where sediment supply is otherwise limited
- May not be most significant external control in some settings

A conceptual model for tidal marsh formation at specific sites contains the hypothesis:

There is a baseline threshold elevation at which initial dominant processes diverge, with a mix of biological (vegetation colonization) and physical (mineral sedimentation) processes above and predominantly physical processes below. This elevation, which varies around the estuary, is the depth to which plants grow and is salinity moderated.

Site characteristic such as degree of subsidence, geomorphology, existing plants and substrate suitability for target flora and fauna are part of the conceptual model affecting baseline threshold elevation. In the conceptual model, channels are the conduits through which water-transported organic and inorganic materials enter, exit, and circulate within the tidal marsh as well as habitat for fish, invertebrates, etc. Each feature of the marsh provides habitats for numerous flora and fauna species. Finally, surroundings can be quite varied but significantly affect marsh function.

Siegel then described specific site characteristics for Suisun Marsh restoration.

1. Establish tidal connections:

a. Full, unrestricted tidal exchange is the hallmark of every successful tidal marsh restoration project

b. Geometry for levee breach(es) considers the larger as-built as well as smaller "equilibrium" tidal prism

c. Levee breach siting considers external and internal factors, such as currents, winds, adjacent properties, extant channel networks, current topography and the like

2. Reversing subsidence - a big challenge

   a. Degree of subsidence varies within and between properties

   b. Common "wisdom" says on the order of ~1 to 4 feet; greater at some sites (Van Sickle, Montezuma, others?)

   c. We need good data on existing topography at the site scale for individual projects and at the marsh scale for regional planning.

   d. Subsidence reversal is affected by

      i. Natural sedimentation

      ii. Vegetation - peat accumulation and sediment trapping

      iii. Fill placement such as dredged material

      iv. Muted regimes with water control structures to lower effective intertidal elevations

3. Establishing channel networks

   a. Extent of preserved historic channel network varies based largely on intervening land use since diking

   b. Suisun Marsh mainly managed wetlands:

      i. Many new ditches constructed to manage water circulation

      ii. Borrow ditches around perimeter levees from construction and maintenance

      iii. Grading typically removes channels wholly or partially

   c. Tides and sedimentation tend to adopt morphology at breaching

   d. Methods for re-establishing channel network depend largely on the amount of subsidence and degree of site modifications

4. Natural ponds

   a. The tidal marshes of Suisun once supported many ponds with tremendous waterfowl abundance

   b. Is it possible to recreate such ponds within tidal marsh restoration projects that would be naturally sustaining?

      i. Little understanding of processes that formed and maintained ponds historically

      ii. Little understanding of processes that could form and maintain ponds in restoration projects

   iii. Hypersalinity? Avian foraging? No drainage?
   iv. Ripe for investigation.

5. Perimeter levees
   a. a.Options for fate of perimeter levees not providing flood control functions:
      i. Leave in place as strip of upland refuge
      ii. Lower to high (or lower) intertidal marsh height to provide early vegetation colonization sites
      iii. Convert to habitat levees by widening interior side to gentle slopes; may or may not lower original levee

6. Managing exotic species
   a. Plants, invertebrates, fish
   b. Peppergrass (*Lepidium latifolium*) the most significant and clear concern
   c. Pre-emptive establishment of target vegetation?
   d. Ongoing active removal during early colonization?
   e. Ripe for identifying appropriate strategies

7. Flood control
   a. Need to avoid tidal flooding neighboring properties.
   b. In order of presumed lowest to highest flood control requirements (and thus costs) for restoration projects:
      i. Island sites presumably have no flood control implications
      ii. "Peninsula" sites with a small levee length separating neighboring properties require some form of flood control
      iii. Sites with several neighbors and thus greater levee length require greater amounts of flood control effort

8. Infrastructure
   a. Roads, rail, below and above ground utility lines (petroleum pipelines, electrical transmission lines, sewer lines), gas drilling pads
   b. Importance of due diligence to know in advance of property acquisition
   c. Effects highly site specific and range from little or no interference to forcing significant design constraints and/or high infrastructure relocation costs

9. Vector control
   a. Mosquito production presumed lower in tidal marshes assuming design does not create stagnant water areas

   b. Compared to managed marshes, lack of water control structures can complicate resolving stagnant areas
   c. Work with Solano County Mosquito Abatement District early and often

10. Contaminants
   a. A long-recognized desirable function of tidal wetlands are their ability to sequester contaminants from the environment
   b. However, "excessive" accumulation can be a concern
   c. Methylmercury production currently the greatest concern and remains an open question
      i. Currently an active area of research
      ii. Important to develop comparative understanding of net production rates and differences in bioavailability pathways between existing tidal marsh, restored tidal marsh (including rates at different stages of evolution), and managed wetlands

Restoration and the Movement of Water and Dissolved and Particulate Constituents.
Chris Enright of DWR discussed the regional effects of tidal marsh restoration, mainly from the standpoint of its impacts on physical processes. He had the following messages he hoped attendees would take home from the presentation.

Creation of tidal marshes in Suisun Marsh will (1) change marsh "geometry"; (2) affect tidal propagation over a wide area, in turn affecting currents, tidal range, and dispersion dissolved, and particulate constituents. Scientists and managers must understand the physical processes in order to plan for, and evaluate the success of tidal marsh restoration. We are presently deficient in this understanding in the marsh. We are very interested in the dispersion of what Jon Burau labeled "stuff" in the water, and modelers call scalars, i.e. salt, sediment, contaminants, carbon, and planktonic organisms such as algae, zooplankton and larval fish. Tidal forces play a major role in dispersion through shear flow (and turbulence), tidal trapping and tidal pumping. Tidal wetlands restoration (through levee breaching, for example) affects geometry and will affect the way in which tidal action moves particles and dissolved materials and their ultimate fate. In levee breaches, the size, depth and location of the breach(es) will affect geometry and the interaction of shear, trapping and pumping and thus water parcel movement. Levee breaches dissipate tidal energy by imparting additional friction, thus tidal range is generally reduced.

Figure 58 illustrates the modeled effect on salinity of a levee breach at the Sunrise Club. Note that salinity increases near the area of the breach but decreases slightly in the Delta.

Enright speculated about the potential effects of tidal marsh restoration after noting that it will change the geometry, and will change hydrodynamics and dispersive transport characteristics. With respect to organic carbon, restoration may be:

- Good: organic carbon from the restoration project may generally be more bioavailable, and will help fuel the estuarine food web.
- Bad: The carbon can contribute to trihalomethane formation potential and thus be a drinking water quality concern.
- Both, depending on levels and location - understanding transport is the key
- Research needs: Estimates of carbon production, quality, transport

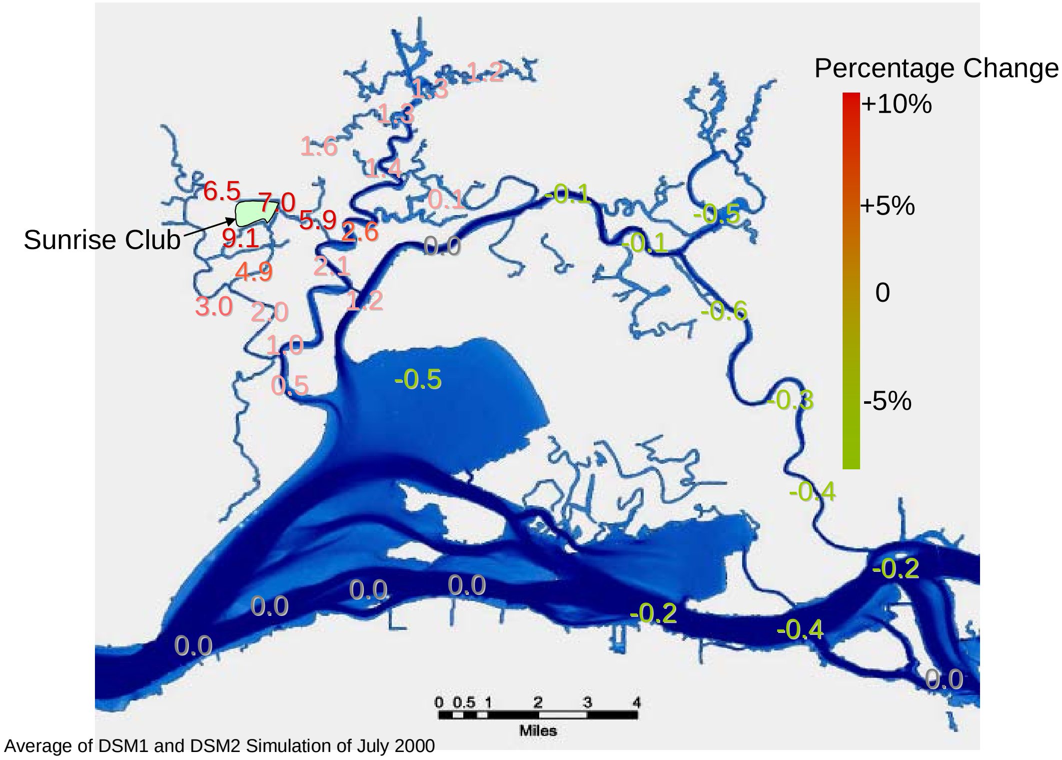

Figure 58. Regional impacts of Sunrise Club levee breaks. (Source: C. Enright.)

If tidal marsh restoration produces fish:

- Good: if the fish are predominantly native
- Bad: if they are predominantly non-native.
- In reality both will be produced.
- Research needs: Does recreated tidal marsh structure and function favor native fish?

If tidal marsh restoration reduces tidal range:

- Good: Takes pressure off levees
- Bad: Affects drainage of managed wetland
- Both: Depends who you ask!
- Research: Location and design of breeches to determine energy dissipation potential

If tidal restoration changes mercury methylation dynamics:

- Bad: If bioavailability is increased there is concern for human and wildlife health
- Good: if CH_3Hg^+ production/reduction relatively less than present.
- Both: will depend on which dominates

- Research
- Land use and spatial extent of oxic-anoxic transition in water or sediment.
- Exposure to what source water, with what phytoplankton concentration, for how long?

Enright's restated take home message,

Tidal marsh restoration:

- Changes marsh "geometry"
- Affects tidal propagation over a wide area
- Produces and consumes good stuff and bad stuff.
- Process understanding is the key to restoration success.

Managed Ponds and Tidal Wetland Restoration. John Takekawa (USGS) used the South San Francisco Bay and Napa-Sonoma salt ponds to illustrate some of the complexities of restoring tidal action to marshes. The estuary supports a wide variety of organisms including shorebirds, waterfowl from the Pacific Flyway, anadromous salmonids, and numerous coastal species. He noted that water diversions, urban growth, environmental contaminants, non-native invasive species, and marsh encroachment were adversely affecting the estuary, including its wetlands.

Figure 59 illustrates the historic, present, and forecasted amount of various kinds of habitat in the San Francisco Estuary - ranging from farmland to mudflats. The important points from this figure are the dramatic loss of wetland habitat to date and the forecast reclamation of some of this habitat. Of particular interest with regard to tidal wetlands is Takekawa's discussion of the proposal to restore (reclaim) significant amounts of habitat by converting salt ponds to ponds that are open to tidal action - the largest wetland restoration outside of the Florida Everglades. There are more than 25,000 acres of salt ponds in public ownership for restoration. Another 10,000 of South Bay salt ponds remain in production. The abbreviated chronology of salt pond development and acquisition for reclamation purposes is shown in Table 12.

As part of the USGS Priority Ecosystems Program, Takekawa and his colleagues have been sampling among and within salt ponds to evaluate the way organisms use the ponds and the importance of the ponds to these organisms. He defined a salt pond as:

- being mesohaline (5-18ppt) to hyperhaline (>300 ppt);
- having irregular to regular flooding (muted tidal flow); and
- lacking emergent vegetation;

and cited tidal marsh ponds, salt lakes, salt pans, salt ponds, and tidal lagoons as examples.

Salt ponds support a wide variety of organisms (Figure 60), with pond salinity affecting the exact species composition. Water depth also helps determine which organisms are found in ponds within each salinity range. In comparison studies baylands were shown to have slightly higher avian diversity but far lower densities than salt ponds. After salt production halted on ponds, birds that fed on the benthos (e.g. diving ducks and canvasbacks) declined while dabbling ducks increased.

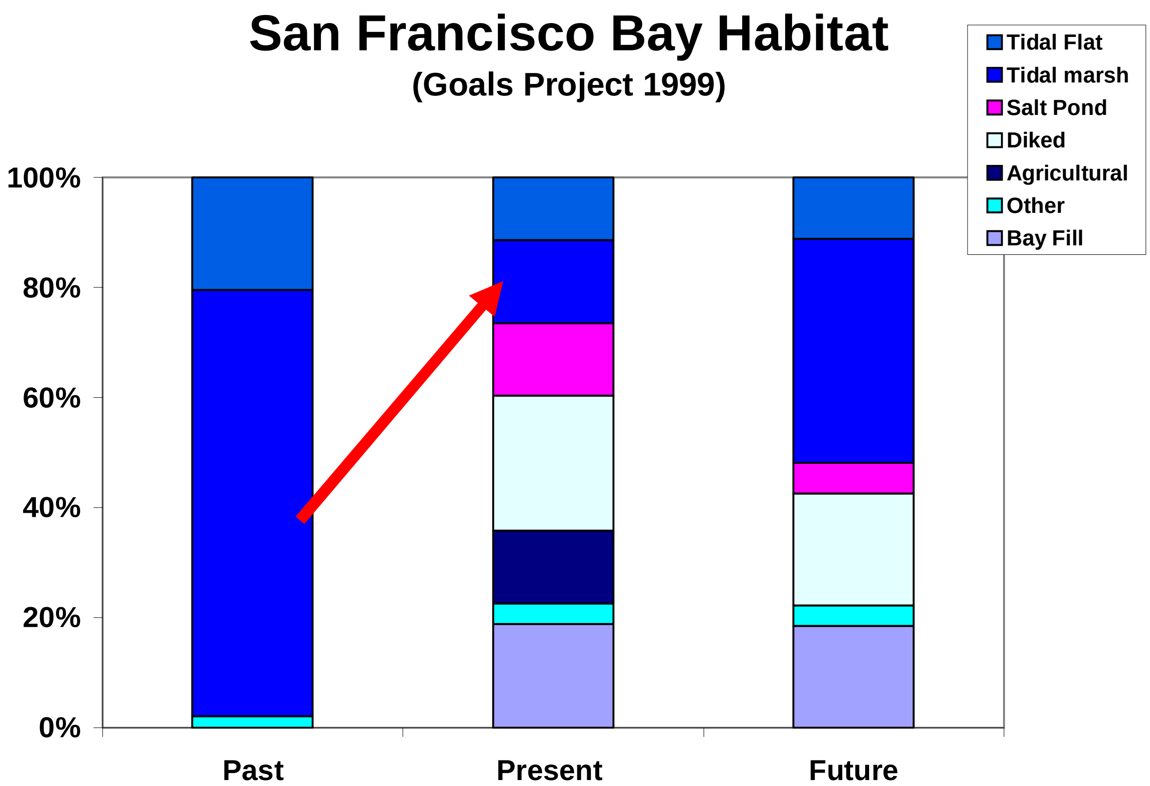

Figure 59. San Francisco Estuary wetland habitat: past and projected future. (Source: J. Takekawa.)

Table 12. Abbreviated chronology of salt ponds and salt pond restoration in the San Francisco Estuary

Year	*Event*
1854	First commercial salt ponds in San Francisco Estuary
1942	Leslie Salt forms from 20 companies 1901-1942
1960	Leslie Salt manages 50,000 acres of salt ponds
1972	San Francisco Bay National Wildlife Refuge created (nation's largest urban wildlife refuge)
1978	Cargill Salt purchases Leslie Salt
1979	San Francisco Bay National Wildlife Refuge purchases 11,430 acres from Cargill (keeps salt production rights)
1994	Cargill sells 10,000 acres of the North Bay to the State of California
2002	Public and private purchase of 16,500 acres approved for $100 million
2003	South Bay Restoration Project (http://www.southbayrestoration.org)

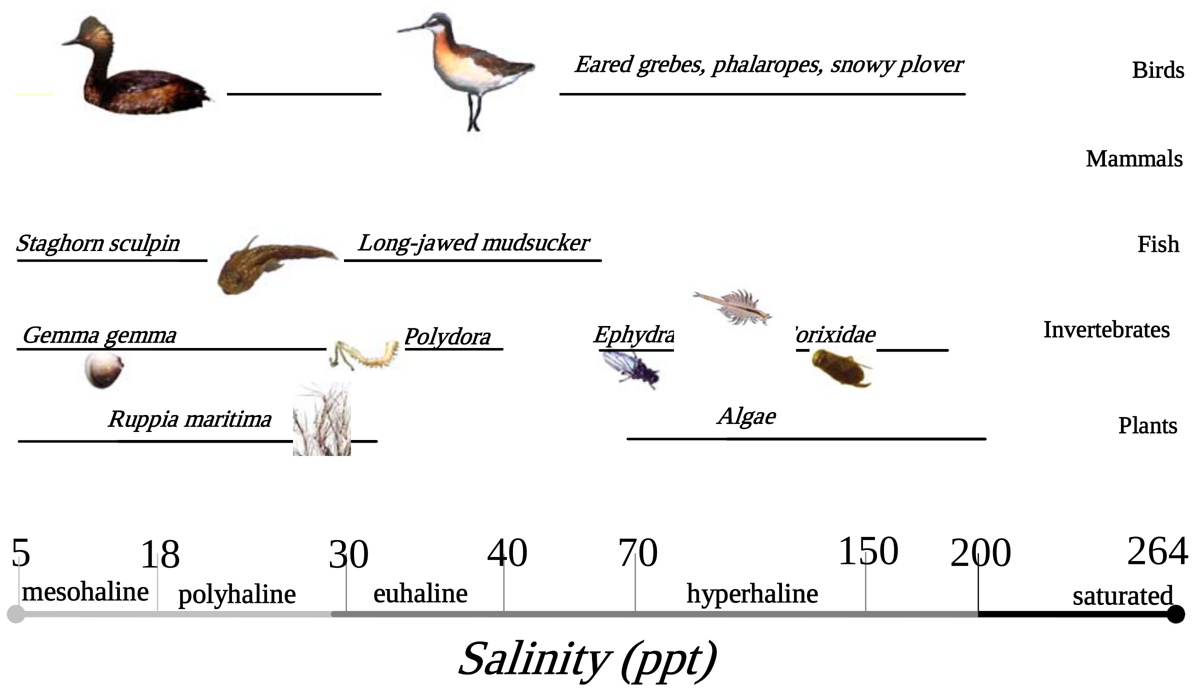

Figure 60. Unique communities and species using San Francisco Estuary salt ponds. (Source: J. Takekawa.)

He presented recent PRBO results to assess the loss of the potential for loss of birds as a result of salt pond conversion. Conversion modeling suggested that:

- Landbirds and rails could benefit greatly from creation of new tidal marsh habitat.
- Loss of salt ponds may cause substantial reduction in waterbird numbers, especially diving ducks and shorebirds.
- Retaining some ponds in a habitat mosaic is critical for migratory birds (more valuable than altering the extent of tidal marsh restoration).

Finally Takekawa and his colleagues used a population viability analysis to look at potential gains from tidal wetlands restoration, with a focus on the San Pablo song sparrow. The conclusions from this work were:

- Historic tidal marshes probably supported three times more song sparrows compared with the present. Proposed restoration will result in increased song sparrow numbers.
- Their analysis indicates little risk of extinction of the San Pablo song sparrow with the current extent of tidal marshes, but with greater vulnerability in the smallest parcels.
- Metapopulation size was directly related to the area of habitat parcels, but not connectivity. Increasing the size of existing fragments is likely more beneficial than increasing corridors between fragments.

As Takekawa pointed out, the benefits of converting salt ponds to tidal wetlands are not as clear cut as they seem. As a result of their studies, and studies by others, the high importance of avian use of salt ponds and other managed ponds has been documented. Managed ponds provide a major component of the wintering habitat for migratory waterfowl and shorebirds in the San Francisco Estuary. Bird use of new tidal wetlands is not as well understood. Takekawa's conclusions on the relative benefits were:

- Managed ponds and salt ponds are valuable wetlands that provide habitats supporting high densities of some species.
- Conversion of existing wetlands may result in increases in some populations (landbirds, rails), but decreases in other populations (shorebirds, waterfowl).
- To optimize resource values, a balance of habitats must be maintained at the regional landscape scale.
- Population viability analyses may be valuable tools to evaluate when it is most beneficial to restore tidal marshes for target species.

Discussion: Restoration Needs, Constraints, and Opportunities

Mary Selkirk led the discussion on this important and complex topic. Below are some of the main points that came out of the discussion.

- There are no ponds in the marsh that are managed the way they were a 100 years ago. Current management ranges from seasonal flooding to some ponds being flooded for 3-5 years. The connection to the estuary is through tidal gates that are used to move water in and out of the ponds.
- There is increasing pressure from urban development around the marsh - including housing development and expansion of landfill. It doesn't take development in the marsh itself to affect the marsh.
- There are issues between landowners and researchers - mainly in the form of allowing access to private lands. There is a gradient of reluctance to allow access, with club owners at both ends of the spectrum. There is a clear communication need to develop trust among the scientists and club owners.
- Researchers need to start specific, hypothesis driven studies right away, probably beginning at a small scale. Also physical and biological scientists need to tell managers and restoration ecologists what restoration activities make the most sense. Some idea of the effects of restoring 5,000 or more acres must be available before taking that big step.
- The regulatory process will slow things down and there will be some club owners concerned about what is happening on neighboring ponds, and how these activities will affect them. It will be difficult to get regulatory certainty but we have deal with listed species protection while trying to optimize waterfowl habitat and production.
- Managers and restoration ecologists must work towards sustainable management actions - not ones that will last only a few years. Sustainability requires that tidal action, sediment supply, sea level rise, subsidence, catastrophic levee failures, organic matter production (and accumulation) and other factors be taken into account when planning and implementing actions.
- Some data gaps:
  - Food availability, needed for models so we can look at food supply and demand realistically.

- – Sedimentation, in the ponds and elsewhere in the marsh. Should include sediment dynamics and fate and the effects of changing land use patterns.
- – Landscape level long term look at physical processes are affecting the marsh.
- – Quantitative estimates of subsidence at different locations in the marsh.

- Long-term data sets may provide useful information and should be considered for detailed examination and analysis.
- We might want to consider marsh restoration in terms of its benefits (or adverse effects) to water project operations.
- The continuation of duck clubs in the marsh depends on the ducks and economics. In most cases this is a short term issue - that is, levee maintenance and other costs of duck club ownership are near term problems. Most duck club owners do not have the luxury of planning on a decadal time scale.
- Water quality standards may need to be tightened in future marsh planning, in particular at a more regional scale.

Science Needs in Suisun Marsh

One take home message from the workshop is that the science base in Suisun Marsh is relatively weak. In this case we define science as hypothesis driven research that leads to results that are published in peer reviewed journals. Many of the presenters cautioned the audience that they had few data on the marsh itself. There was a paucity of specific references to journal publications to support conclusions that might be drawn about the Suisun Marsh system. When moving out into the estuary, the science base becomes stronger and the publication record richer.

There are exceptions to this general rule in Suisun Marsh, especially with respect to fish communities in marsh channels (for example, Matern 2001; Matern and Fleming 1995; Meng and Matern 2001; Meng and Moyle 2001; Matern et al. 2002, plus several Ph.D. dissertations such as Herbold 1987) all coming out of the UC Davis fish monitoring program. In recent years there have been several studies at Rush Ranch involving students from UC Davis and US Berkeley (see for example Byrne et al. 2001). There are also numerous agency reports and newsletter articles that provide useful information but have not been peer reviewed. All in all, however, it is not a bright science picture for the marsh.

Before going into a partial list of information needs and a process that might be used to fill those needs, I would like to describe a promising beginning to an expanded science effort in the marsh. These efforts began shortly after the March 2004 workshop and demonstrate what can be done in a relatively short time and with fairly limited financial resources. The study also demonstrates a collaborative approach to research that may result in the greatest information gain in such complex systems as Suisun Marsh.

The following study description has been adapted from material submitted by Chris Enright of DWR and Jan Thompson of the USGS. Thompson is the leader of the USGS local Place-Based Program efforts that use an interdisciplinary approach to developing an understanding of complex ecological systems. Thompson and her colleagues recently have been working in Suisun Bay and have now expanded their efforts into the marsh. One of the Place-Based goals in the marsh work is to understand the role of the Suisun Marsh as a source or sink of metals, selenium and carbon in the Northern estuary. The USGS will establish three new stations in the marsh (in addition to the four in Grizzly/Suisun Bay) to collect bivalves and other benthic organisms. Tissue samples from these organisms, along with ancillary flow and water data, will be analyzed to estimate fluxes of materials.

A small, multi-agency, multi-disciplinary team collaborated on a pilot study to characterize first order hydrodynamics, and production/consumption/transport of salt, sediment, carbon, and contaminants in the aquatic marsh. This ad hoc program coalesced around a mutually perceived need to expand understanding of an under studied system. Interdisciplinary collaborators came from USGS - Menlo Park, UC Davis, DWR - Division of Environmental Services (DES), DWR - Central District, USGS - Sacramento, and DFG - Moss Landing. The IEP provided $25,000 for seed funding. DWR DES provided funding to UC Davis ($50,000) and DWR Central District ($70,000). Other collaborators brought their own funding. Monitoring equipment was borrowed from the IEP's Environmental Monitoring Program (EMP), UC Berkeley, USBR, and equipment manufacturers. Collaborators freely shared boats, equipment, and personnel. The IEP EMP program provided essential start-up expertise.

An *in situ* monitoring program was deployed at thirteen key locations in the Suisun Marsh (Figure 61). The *in situ* program was designed to:

1. Measure the timing and magnitude of currents at key locations in the marsh.
2. Estimate the flux of salt, temperature, sediment, chlorophyll, and contaminants between Suisun Marsh and Suisun Bay.
3. Estimate the production/consumption of sediment, chlorophyll, and contaminants from different watersheds (land uses) within the marsh.
4. Measure tidal and residual current patterns to validate hydrodynamics and transport models.
5. Determine methods and equipment needed to answer aquatic habitat science questions that will inform future restoration initiatives.

In addition, USGS Menlo Park (Brown, Thompson, Luoma) expanded their contaminants monitoring program into the marsh by co-locating benthic sampling sites with the in situ monitoring locations. UC Davis (Schroeter, Moyle) co-located CALFED funded zooplankton monitoring with the in situ instruments and collaborated with USGS and DWR on tidal cycle passive drifter experiments. DFG Moss Landing (Stevenson) deployed tidal cycle auto-samplers at in situ instrument locations to measure water column methyl mercury.

Preliminary data indicate that the marsh is exporting carbon to the estuary. Data analysis will pursue the hydrodynamic, chemical and biological mechanisms for this production to inform future restoration actions.

To help identify data gaps, I extracted the following list of information needs from the presentations. The list is not in any particular order of priority and most certainly is not complete. As will be seen the science needs vary from monitoring to hypothesis driven research. Overall the information needs (aka data gaps) should focus on studies that will help elucidate processes and increase the reliability of conceptual and mathematical models.

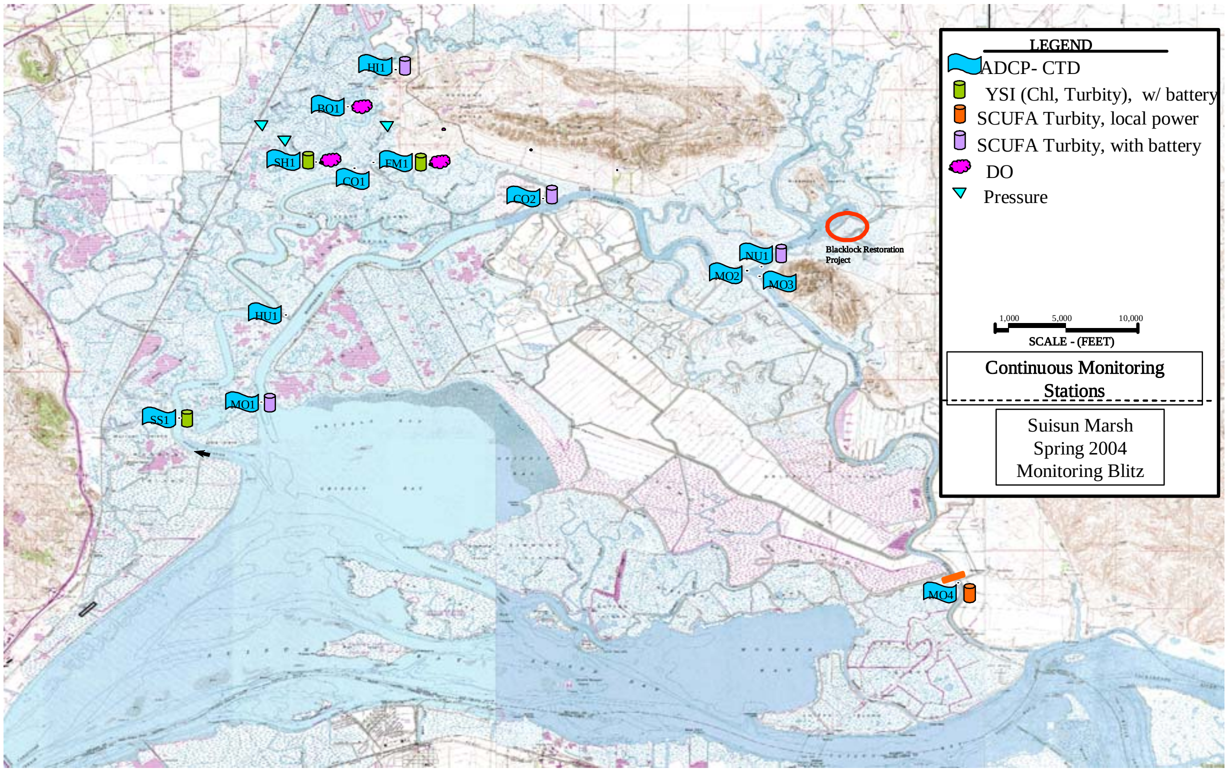

Figure 61. Continuous monitoring station locations from spring 2004 monitoring blitz. (Source: C. Enright and Thompson.)

Some data gaps listed by workshop speakers

- Water movement into and with marsh channels and how does it vary with flows, tides, and structures. These data are needed for many purposes, including calibration and verification of mathematical models.
- Contaminants. We had no presentations on contaminants at the workshop. Although there has been some work done on mercury in the marsh, the contaminant field is relatively wide open.
- Biogeochemical and morphological processes
  - Comparative land use studies of soils characteristics, biogeochemical cycling, and ecosystem functions
  - Accurate, fine-scale elevation data describing Suisun Marsh intertidal elevations and soil surface directional tendencies
  - Organic matter/carbon production and storage rates
  - Suisun-specific subsidence rates
  - Regional rates of ground surface movement
  - Local/regional groundwater characterization
  - Sediment movement and deposition rates into and within Suisun Marsh.

- Effects of restoring habitat to tidal marsh on breeding and production
- Duckling habitat use and survival, affects of salinity
- Productivity in marsh channels
  - – Are more interior sloughs a “productivity refuge?”
  - – Based on food resources in the channels, what are appropriate restoration targets?
  - – What is the relative importance of new zooplankton and benthos in the channels?
  - – All questions about the effects of introduced species on the system.
- Otters in Suisun Marsh
  - – How do they use the space?
  - – What is the impact of their opportunistic feeding on waterfowl and other vertebrates?
  - – Can the local environment be managed to enhance their persistence?
  - – What is the impact of contaminants in the water?
  - – What does their biology in the marsh tell us about otters in general?
- Effects of construction and other activities in and near the marsh
  - – Proposed Highway 680/80 Bypass
  - – Petroleum Product Transmission Pipelines
  - – Urban Encroachment
- Information needs from a the private duck club perspective
  - – Identify opportunities for new marsh management strategies
  - – Enhancement of existing wetland values and functions
  - – Compatibility with ESA/native species recovery
  - – Evaluation of existing managed wetland waterfowl food resource production and availability
  - – Comparisons of managed wetlands resource values to tidal wetlands and tidally restored areas
  - – Improve understanding of soil chemistry, leaching, and the acid sulfate soil reactions
- Information needs for rails in the marsh
  - – Annual abundance surveys
  - – Science-based restoration designs
  - – Demographic information
  - – Predator effects and control
  - – The extent and suitability of existing habitat
  - – What can be done to enhance existing habitat?
  - – How do we identify and protect source populations?

- Waterfowl feeding in the marsh
- Information on food densities in Suisun Marsh habitats both tidal and non-tidal
- Ecological contribution of Suisun Marsh to the broader San Francisco Estuary system
- What is the present marsh contribution (as it varies temporally) of organic materials, fish and avian habitat, etc. to the San Francisco Estuary and how will this contribution change as more tidal habitat is created in Suisun Marsh?

To establish priorities and implement studies responding to the above and other science needs, I propose that the Charter Group's Suisun Marsh Technical Team (or some other entity with an overall science role in the marsh - the IEP?) be charged with developing a marsh science agenda. Such an agenda would be a logical outgrowth of the team's current conceptual modeling efforts. The following points should be considered when developing the science agenda.

- A critical review of existing information. This workshop summary, the powerpoint presentations posted on the BDSC website and discussions with the individual presenters can provide additional suggestions as to where science is needed. The Suisun Ecological Workgroup final report and independent work team reports should be mined for its wealth of information on the marsh and its data needs. The Charter Group's conceptual models, as well as those described in this report will indicate where data are limited and a sense of the priority for filling the data gaps.
- A useful place to start might be the components of the original conceptual model of how the marsh operates in terms of waterfowl production - that is the George, Mall, Rollins information base that was used to develop marsh management and mitigation requirements. In the conceptual modeling section of this report, Enright has already begun to examine the long term salinity record and the effects of water project operations on the salinity of water entering the marsh. Burns et al. (2003) used more modern and scientifically rigorous methods to examine the food habits of three ducks using the marsh as wintering and nesting habitat. The whole field of salt, soil, water management and plant growth is ripe for research.
- Consider the geomorphologic processes, including sediment supply and the oxidation of organic soils, as identified in the conceptual model by Culberson and Enright in this summary. Subsidence, as affected by natural and pond management practices, is one of the most important issues in the marsh.
- Any science agenda should consider the implications of the changing climate, and its effects on sea level and runoff patterns, as are being elucidated by Dettinger and his colleagues.
- CALFED Science Program's just released Proposal Solicitation documents and its accompanying document on Science Implementation contain valuable information on the components of successful science agenda and some key questions that need to be answered in understanding and managing resources of the San Francisco Estuary and its watershed. The Science Implementation document includes an appendix containing thoughts on a Suisun Marsh science agenda.
- Consider the use of outside experts, either singly or in panels, to assist in developing a science agenda. Workshops, white papers, conceptual models can all provide the background information necessary to maximize their contribution.
- Consider periodic (annual?) Suisun Marsh workshops to highlight the state of the science in the marsh and/or special Suisun Marsh sessions at the biennial CALFED Science Conference, State of Estuary Conference and the IEP's annual workshop.

- Consider publishing scientific papers on marsh studies in the open literature, including the new electronic journal, San Francisco Estuary and Watershed Science.
- Finally, Suisun Marsh managers, planners, and scientist must recognize that developing a Suisun Marsh science agenda is not a trivial undertaking. Realistically it will take at least one to two years to come up with a consensus agenda. In the meantime, consider submitting specific proposals to the CALFED Science Program or Ecosystem Restoration Program Proposal Solicitation Process announcements. A recent proposal by Siegel et al. (2002) and Bollens et al. (2002) on wetland restoration monitoring provides a useful example of how responses to the PSP could be structured. Collaborative research proposals might be developed to take advantage of the IEP/DWR/USGS/DFG/UCD pilot program described above.

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Appendix A: Attendance List

Name	Organization
Ackerman, Josh	USGS
Alendor, Cigden	UCD
Arnold, Tony	SRCD
Baron, Sandra	Ecologic Consulting
Barton, Jennifer	Representative Tauscher
Belfiore, Natalia	UCB
Bellmer, Russ	FWS
Blegen, Jon	SCMAD
Bohannon, Scott	?
Bowles, Chris	PWA
Brand, Marina	DFG
Briden, Laurie	DFG
Brosnan, John	Bay Area Wetalnds Restoration Program
Brown, Cecilia	FWS
Brown, Cindy	USGS
Brown, Larry	USGS
Brown, Randy	CALFED / DWR
Bruce, Kristin	SRCD
Burau, Jon	USGS, water resources division
Burmester, Daniel	DFG
Burns, Ed	CWA
Buss, Stephanie	DFG
Castillo, Ganzalo	USFWS
Chadwick, Pete	DFG
Chappell, Steven	SRCD
Connolly, Terry	SRCD
Conomos, John	BDSC
Culberson, Steve	DWR
Davis, Doug	?
Dettinger, Mike	USGS
Doyle, Albert	Ghostwriters
Duncan, Jeanne	Ghostwriters
Eadie, John	UCD
Eddings, Robert	CWA
Enos, Cassandra	DWR
Enright, Chris	DWR
Estrella, Sarah	DFG

Evens, Jules. Avocet Research Associates
Fallscheer, Robin .DFG
Farwell, Jane .SWRCB
Feyrer, Fred. DWR
Fien, Chad. . . . . .DFG
Florsheim, Joan. UCD
Fong, Bellory . . . . CBDA
Fox, Chris . . . . DWR
Frost, Mike . . . . Frost Consulting
Fujii, Roger .USGS
G., Steve . . . .
Gaines, Terri . . . . DWR
Garrison, Paul .DFG
Ger, Ali . . . . UCD
Goude, Cay .FWS
Green, Greg. DU
Grewell, Brenda . . . . UCD
Groeden, Brenda . . . . BCDC
Grossinger, Robin .SFEI
Haffner, Craig . . . . SRCD
Hanson, Chuck . . . .
Hardwick, Jim. . . . . .DFG
Hart, Jeff . . . . Hart Restoration, Inc.
Hastings, Lauren . . . . CALFED
Hickey, Catherine . . . . PRBO
Hymanson, Zachary . . . . CALFED Science Program
Jones, Conrad .DFG
Kaff, Darrel. DWR
Keeler-Wolf, Todd .DFG
Kelly, Mike . . . . SEENO
Kiparsky, Mike . . . . CBDA
Kitting, Chris . . . . CSUH
Kuivila, Kathy. . . . . .USGS
Laurence, Lee . . . . USBR
Lentz, Ken. USBR
Litman, Laurie . . . .
Long, Jim . . . . DWR
Lougee, Ladd . . . . BDSC
Machula, Jana . . . . CBDA
Malamud-Roam, Frances .UCB

Manza, Peggy . . . . .BOR
McInerey, Jack . . . . Duck Club Owner
Meisler, Julian. . . . . Solano Land Trust
Minn, Ken . . . . DWR
Monaghan, Jodie. . . . . CCP
Moore, Tom . . . . NRCS
Moyle, Peter . . . . UCD
Mueller-Solger, Anke . . . . DWR
Nelson, Kent . . . . DWR
Nichols, Fred. . . . . USGS, retired
Nogur, John. . . . . Solano Community College
Nur, Nadav . . . . PRBO
O'Connor, Mike . . . . .Suisun Marsh Sweetwater Duck Club
Oldenburger, Shaun . . . . UCD
Ostruff, Ruth . . . . USFWS - Central Valley
Pacheco, Victor . . . . DWR
Parchaso, Francis . . . . .USGS
Patterson, Elizabeth . . . . DWR
Patterson, Laura . . . . DWR
Pawley, Anitra. . . . . TBI
Petrie, Mark . . . . Ducks Unlimited
Porter, Treva . . . . .DFG
Quickert, Patty . . . . DWR
Ray, Dan . . . . CBDA
Reed, Rhonda . . . . CBDA
Ridley, Erik. . . . . US House of Reps
Robles, John . . . . USBR
Rosen, Rudy . . . . .DU
Rousseau, Denise . . . . ESA
Schmidt, David . . . . USEPA
Schmutte, Curt . . . . DWR
Schoellhamer, Dave . . . . USGS, WRD
Schroeter, Robert . . . . UCD
Selkirk, Mary . . . . Center for Collaborative Policy
Shabel, Alan . . . . .UCB
Shaffer, Bob . . . . CVHJV
Shouse, Michelle. . . . . .USGS
Showers, Dave . . . . DWR
Siegel, Stuart. . . . . .WWR
Sihut, Edward . . . . DWR

Smith, Dan	Benicia City Council
Smith, Lawrence	USGS
Smith, Tara	DWR
Snow, Mary	SFSU
Stover, Ali	UCD
Sullivan, Bernici	WVA
Sullivan, Joe	UCD
Sustaita, Diego	DFG
Swenson, Ramona	Nature Conservancy
Takekawa, John	USGS
Taplin, Justin	Hanson Environmental
Thompson, Jan	USGS
Thompson, Laureen	DFG
Todowolf, Jeff	Land Owner
Totzke, Kane	KCWA
Van Klompenburg, Gina	DFG
Vayssieres, Marc	DWR
Warnock, Nils	PRBO
Waters, Jim	SRCD
Webb, Kim	USF&WS
Wernette, Frank	DFG
White, Sandra	DFG
Wickland, Bruce	
Wilcox, Carl	DFG
Williams, Phil	PWA
Withrow, Bud	Wings Landing
Zezil, D.S.	DFG

Appendix B: Agenda

Making Science Work for Suisun Marsh
1st Floor Auditorium
Employment Development Department Building
722 Capitol Mall, Sacramento, CA

Day 1: March 1, 2004

Introduction and Context

09:00 John Conomos (BDSC) .... Welcome

09:10 Laurie Briden (DFG) .... The Suisun Marsh; current conditions, general operations atlas, and adjacent land use trends

09:40 Robin Grossinger (SFEI) .... What does the history of Suisun Marsh tell us about its future management?

10:10 Pete Chadwick (DFG, emeritus) .... Policy history

10:30 BREAK

10:45 Victor Pacheco (DWR) .... Current status

11:00 Zach Hymanson (CBDA) .... Conceptual models

11:15 Frank Wernette (DFG) .... Facilitated discussion

11:45 LUNCH BREAK .... (4th Floor Cafeteria)

Physical Processes

12:30 Frances Malamud-Roam (UCB) .... A 2500-year paleosalinity record from Rush Ranch in Suisun marsh in the San Francisco Bay estuary

12:50 Jon Burau (USGS) .... Transport in Suisun Marsh - Why do we care and what do we know?

13:10 Chris Enright (DWR) .... Long-term trends and variability of Suisun Bay and Marsh salinity

13:30 Dave Schoellhamer (USGS) .... Lessons from studies in similar systems

13:50 Steve Culberson (DWR) .... Suisun Marsh geomorphologic process, ecosystem function, and contemporary management practices

14:10 BREAK

14:30 Roger Fujii, Brian Bergamaschi, Jacob Fleck, Steve Deverel, and Karen Burow (USGS) .... Dissolved organic carbon in the Delta: loads and quality from agricultural operations and wetlands

14:50 Mike Dettinger (USGS) .... Climate change and runoff; predictions for the next century

15:10 Chris Enright and Steve Culberson (DWR) .... Presentation of conceptual models

15:40 Zach Hymanson (CBDA) .... Facilitated discussion

17:00 SOCIAL

Day 2: March 2, 2004

Aquatic Ecology

8:30 Peter Moyle (UCD) .... Introduction

8:35 Anke Mueller-Solger (DWR) .... The base of the aquatic food web in Suisun Marsh

8:55 Robert Schroeter (UCD).. Aquatic invertebrates of Suisun Marsh sloughs

9:15 Peter Moyle (UCD) .... Fishes of Suisun Marsh

9:35 Natalia (Tasha) Belfiore (UCB)........................... Otters: the charismatic predator of Suisun Marsh

9:45 BREAK

Terrestrial Ecology

10:00 Frank Wernette (DFG)..Sub-section introduction

10:02 Todd Keeler-Wolf (DFG)....... Vegetative composition of Suisun Marsh and some of it's rare plants

10:15 Josh Ackerman (UCD) ....Wintering and breeding waterfowl of Suisun Marsh

10:30 Mark Petrie (DU)......................................Waterfowl food habits and current role of Suisun Marsh in the Pacific Flyway

10:45 Jules Evens (ARA) ....Rails and large wading birds of Suisun Marsh

11:00 Nadav Nur (PRBO) .... Songbirds and shorebirds of Suisun Marsh

11:15 Diego Sustaita (CSUN) .... Suisun Marsh mammals; emphasizing the salt marsh harvest mouse

11:30 Group presentation .... Food webs, limiting factors, and ecosystem structures: conceptual models for Suisun Marsh

11:45 Frank Wernette (DFG)..Facilitated discussion

12:30 LUNCH BREAK

Applied Resource Management: Managed Wetland and Tidal Marsh Restoration

13:15 Steven Chappell (SRCD).....Managed wetlands seasonal operation and habitat management goals. Constraints and opportunities in wetland management.

13:30 Victor Pacheco (DWR).. Suisun Marsh water management infrastructure

13:45 Stuart Siegel (WWR)......... Conceptual model, goals, and site factors for tidal marsh restoration in Suisun Marsh

14:10 Chris Enright (DWR)....Regional effects of tidal marsh restoration in Suisun Marsh - salinity, tidal prism, and levees

14:30 John Takekawa (USGS)...Managed ponds vs. tidal marsh: a comparison of waterbirds in S.F. Bay and salt ponds

14:45 BREAK

15:00 Mary Selkirk (CCP)..Facilitated discussion

16:00 John Conomos (BDSC) . Resource management needs, interdisciplinary studies, workshop closure

16:45 End

Appendix C: Notes for Draft Conceptual Model: Carbon Sources, Sinks, and Pathways in Suisun Marsh

Lines and Symbols:

Dotted Line: Suisun Marsh Boundary
Boxes: Carbon Reservoirs/Sources-Sinks
Solid Arrows: Carbon Transport Pathways (Physical)
Broken Arrows: Carbon Transformation and Trophic Transfer Pathways (Chemical/Biological)
Red Circles: Human Management Actions
Yellow Triangles: Environmental Forcing Factors

Explanations:

Carbon Reservoirs/Sources-Sinks (Boxes):

- Atmosphere: Carbon is abundant, occurs mostly as CO_2
- Watershed water: Carbon in water from major tributaries (Sacramento & San Joaquin Rivers) and local streams. Carbon occurs as Dissolved Inorganic Carbon (DIC: dissolved CO_2, bicarbonate (HCO3-), and carbonate (CO32-)), Dissolved Organic Carbon (DOC), and detrital (dead) organic carbon particles (often referred to as Particulate Organic Carbon, POC). Carbon in watershed water can also be in the form of living organisms. For the purpose of this conceptional model, this carbon fraction is treated separately, see "biota." Organic carbon brought into Suisun Marsh from the watershed is referred to as "allochthonous carbon."
- Water exports: Carbon in water exported through the water project export facilities is drawn through part of the Suisun Marsh watershed, the Delta. Carbon occurs in the same forms as in the watershed water.
- Ocean water: Carbon in ocean water. Carbon occurs in the same forms as in the watershed water. It is exchanged with the marsh water through the tides.
- Suisun Marsh water (Main Slough Channel (MSC) water, Managed Wetlands (MW) water, Tidal Marsh (TM) water): Carbon occurs in the same forms as in the watershed water. Organic carbon produced in Suisun Marsh is referred to as "autochthonous carbon."
- Terrestrial Biota: Organic carbon biomass in the form of organisms living in or on soils or in the atmosphere.
- Aquatic Biota: Organic carbon biomass in the form of organisms living in water (pelagic organisms) or sediments (benthic organisms).
- Sediments: Sediments underlie more permanent marsh water bodies (tidal sloughs, ponds) and can have fairly large proportions of inorganic material brought in from the watershed.
- Soils: Soils underlie areas that often dry out (marsh plain, very small sloughs, slough margins) and intermittent marsh water bodies (duck ponds). Suisun Marsh soils can have large proportions of organic material produced in the marsh.

Human Management Actions (Red Circles):

1. River flow regulation through reservoirs, diversions/exports, levees and canalization, flood control structures, etc.

2. Alteration of tidal excursions/fluxes through river flow regulation, tide gates, salinity control structures, etc.
3. Manipulation of water flow direction through export pumps in south-western Delta.
4. Alteration of exchanges between main slough channels and marsh plain/pond water through blockage of natural exchanges by levees and managed exchanges using tide gates, pumps, etc.
5. Alteration of exchanges between main slough channels and marsh plain/pond biota through blockage by levees, managed exchanges using tide gates, pumps, etc, and active food crop management to benefit certain (duck) species

Environmental Forcing Factors (i.e. external environmental factors affecting carbon cycling in Suisun Marsh and carbon transports into and out of Suisun Marsh water (yellow triangles):

1. Climate: amount and timing of precipitation affects river flows and thus water and carbon transport from the watershed to Suisun Marsh. River flow/residence time, river temperature, and associated nutrient and dissolved oxygen dynamics also affect carbon productivity and trophic transfer dynamics in the watershed, thus modulating the supply of allochthonous carbon to Suisun Marsh.
2. Climate and tides: extent and timing of tides and river flows affects water and carbon export from Suisun Marsh upstream into the watershed and Delta and downstream into the ocean. It also affects other water quality aspects important for carbon production and cycling in Suisun Marsh such as dissolved oxygen, inorganic nutrients, salinity and temperature.
3. Climate and tides: extent and timing of tides and river flows affects carbon production in the ocean and San Francisco Bay and carbon transport and water flows upstream into Suisun Marsh.
4. Gravity, chemical gradients, climate, and tides: these factors influence organic carbon production in the water column, sediments, and soils. They force carbon compounds to settle out of the water column or the atmosphere and (along with water) seep into or get buried in the sediments and soils and eventually leave the sediments and soils again via respiration and leaching. They also affect other water quality aspects important for carbon production and cycling. Oxygen plays a particularly important role: in its presence, organic carbon leaves the soils/sediments via respiration (oxidation) when it is present and by forcing organic carbon accumulation in the soils/sediments when it is absent.
5. Concentration gradient between CO_2 in the atmosphere and CO_2 in water, soils, and biota.

Carbon Transport Pathways (Solid Arrows):

A. Riverine transport of carbon (DIC, DOC, particulate detritus, and living biota) from the Suisun Marsh Watershed to Suisun Marsh Main Sloughs.

B. Tidal transport of carbon from Suisun Marsh Main Sloughs upstream into a portion of its watershed. Also transport via migrating animals.

C. Transport of carbon from Suisun Marsh Main Sloughs upstream into the Delta toward the water export pumps.

D. Carbon export from Suisun Marsh Main Sloughs to the ocean via riverine outflow, tidal fluxes, and migrating animals.

E. Tidal transport of carbon from the ocean to Suisun Marsh Main Sloughs with the tides and through migrating animals.

F. Managed tidal/ riverine or pump exchange of non-living carbon (DIC, DOC, particulate detritus) between Suisun Marsh Main Sloughs and managed wetlands (MW) through tide gates and artificial channels during specific times of the year.

G. Natural, year-round tidal/ riverine exchange of non-living carbon (DIC, DOC, particulate detritus) between Suisun Marsh Main Sloughs and tidal marshes (TM) through small tidal channels and across the marsh plain and ponds at high tides.

H. Managed tidal/ riverine or pump exchange of biota (biomass carbon) between Suisun Marsh Main Sloughs and managed wetlands (MW) through tide gates and artificial channels during specific times of the year. Also exchange through animals migrating across levees.

I. Natural, year-round tidal/ riverine exchange of biota between Suisun Marsh Main Sloughs and tidal marshes (TM) through small tidal channels and across the marsh plain and ponds at high tides.

J. Transport of non-living carbon (DIC, DOC, particulate detritus) from Suisun Marsh sediments to Suisun Marsh through physical resuspension and biological transport.

K. Transport of non-living carbon (DIC, DOC, particulate detritus) from Suisun Marsh Water to the underlying sediments through physical sedimentation and biological transport.

L. Transport of non-living carbon (DIC, DOC, particulate detritus) and biota from the sediments underlying more permanent marsh water bodies (small and large sloughs, fairly permanent ponds) to the surrounding soils through seepage, biological transport, and anthropogenic perturbation.

M. Transport of non-living carbon (DIC, DOC, particulate detritus) and biota from Suisun Marsh soils to the sediments underlying more permanent marsh water bodies through seepage, biological transport, and anthropogenic perturbation.

N. Transport of terrestrial biota and terrestrially derived detritus to and from Suisun marsh water bodies.

O. Transport of terrestrial biota and terrestrially derived detritus to and from Suisun marsh soils.

<u>Carbon Transformations and Trophic Transfer Pathways (Broken Arrows):</u>

1. CO_2 exchange between the atmosphere (CO_2) and watershed, ocean, and Suisun Marsh water (Dissolved Inorganic Carbon, DIC (dissolved CO_2, bicarbonate (HCO_3^-), and carbonate (CO_3^{2-})

2. Transformation of atmospheric CO_2 to organic carbon (biomass) through photosynthesis and of organic carbon to atmospheric CO_2 through respiration (carbon oxidation) by terrestrial biota (terrestrial biota include soil organisms; similar pathways as in 3 occur, requires oxygen and/or light).

3. Biological and chemical transformation and transfer of carbon by aquatic biota in the water column and sediments of Main Marsh Sloughs (MSL), Managed Wetlands (MW), and Tidal Marshes (TM) in Suisun Marsh. Many transformations require oxygen and/or light.

a. Primary production: photosynthetic transformation of DIC to organic carbon (biomass) by algae and Submerged Aquatic Vegetation (SAV). Algae include benthic and pelagic algae and cyanobacteria. Requires light.

b. Trophic transfer of autotrophic producer into animal biomass through animal feeding. Animals include pelagic and benthic metazoan consumers and phagotrophic protozoa. Requires oxygen.

c. Trophic transfer of autotrophic producer into microbial biomass through microbial degradation of algal and SAV exudates and biomass. Microbes include pelagic and benthic heterotrophic bacteria, osmotrophic protozoa, and fungi. Requires oxygen.

d. Trophic exchange of microbial and animal biomass through animal feeding on microbes and microbial degradation of animal secretions and biomass. Requires oxygen.

e. Trophic transfer of Dissolved Organic Carbon (DOC) into microbial biomass through microbial uptake of DOC.

f. Release of DOC by aquatic biota through secretion, lysis, and biomass degradation.

g. Transformation of DOC to DIC through microbial respiration and photolysis. Requires oxygen and/or light.

h. Conversion of living organic carbon (biomass) to detrital organic carbon particles (also know as Particulate Organic Carbon, POC) through death of biota and mechanical, chemical, and biological disintegration and degradation.

i. Trophic transfer of particulate detrital organic carbon particles into animal biomass through animal feeding. Requires oxygen.

j. Conversion of detrital organic carbon particles to DOC through microbial and chemical degradation and photolysis. Requires oxygen and/or light.

k. Transformation of detrital organic carbon particles to DIC through consumer respiration and photolysis. Requires oxygen and/or light.

4. Conversion of DOC to detrital organic carbon particles through flocculation.

5. CO_2 exchange between the atmosphere (CO_2) and Managed Wetland soils (especially peat) through respiration, diffusion, and photolysis (requires oxygen and/or light).

6. CO_2 exchange between the atmosphere (CO_2) and Tidal Marsh Soils (especially peat) through diffusion, respiration, and photolysis (requires oxygen and/or light).