PRELIMINARY REPORT

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Sacramento/San Joaquin Delta Breached Levee Wetland Study (BREACH)

BREACH Interdisciplinary Research Team

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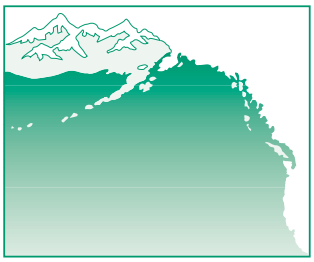

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KEY WORDS

breach, habitat restoration, hydrogeomorphology, insects, invertebrates, levees, non-indigenous species, pennywort, Sacramento–San Joaquin Delta, San Francisco Bay, salmon, sedimentation, water hyacinth, wetlands
Other key words to be provided for final report.

EXECUTIVE SUMMARY

Over 90% of the once vast tidal–freshwater wetlands of the Sacramento–San Joaquin Delta have been leveed and removed from tidal and floodwater inundation. To meet one of its major goals of "restoring ecosystem health," the California Federal (CALFED) Bay/Delta Program is considering restoration of a significant portion of these tidal wetlands by breaching and removing the levees around delta islands. A major goal of this restoration is to promote a diverse native fish assemblage, which in the delta has undergone significant reduction in population numbers in recent years. Restoring shallow-water habitat may promote primary productivity and increase spawning, rearing, and refuge habitat for native fish. The objective of our BREACH research project was to test the underlying assumptions upon which this restoration strategy is based, and to generate quantitative predictions of the patterns and rates of restoration for shallow-water habitat and tule marsh in the delta.

In 1997, we assembled our team of coastal ecologists (University of Washington), geomorphologists (University of New Orleans), hydrologists (Philip Williams and Associates) and fisheries biologists (California Dep. Water Resources) to analyze historically breached-levee wetlands as a means to predict the feasibility, patterns, and rates of restoration to natural ecological function. Breached-levee sites are former natural, freshwater tidal wetland areas that were leveed in the past and have now reverted to tidal action. We compared physicochemical and ecological indicators of wetland status at sites that were accidentally or purposefully constructed by levee breaching, often with supplemental actions such as dredge material disposal. Using the same indicators, we compared the status of both these naturally and intentionally restored wetlands to the few natural "reference" wetland sites remaining in the delta. These reference wetlands provide templates of habitat complexes (tule marsh, woody riparian vegetation, submerged and floating aquatic vegetation, tidal channel geomorphology, etc.) that we hypothesize the modern delta ecosystem can sustain.

On the basis of prior knowledge and our initial results, we have developed a conceptual model of the evolution of freshwater–tidal wetland geomorphology within breached-levee sites in the Sacramento–San Joaquin Delta. Our focus in this model was on the patterns and rates driving development of the tule marshplain because it is the predominant historical and present habitat type in reference sites, and because it is the target of many wetland restoration initiatives in the delta. Given that diking delta islands causes major subsidence relative to sea level, the key factor in restoring tule marshplain is generating intertidal habitat that can be colonized by tule vegetation. Some of the breached sites had subsided up to 6 m during the time they were leveed. Our examination of breached-levee sites in the delta indicates that freshwater–tidal marsh vegetation colonizes bare ground at intertidal elevations within several years. Vegetation establishment through natural processes on deeply subsided, subtidal areas takes significantly longer—as long as several hundred years—because of slow accretion of sediments and organic matter. Artificial means of raising bed elevations, such as deposition of dredged materials, accelerates vegetation establishment. While processes involved in establishing marsh vegetation at intertidal elevations are evident, we need to better understand the mechanisms and rates of transition between subtidal and intertidal habitats, and the role of submerged and floating aquatic vegetation (SAV and FAV) in this process.

Our emerging information on vegetation change, marsh surface accretion, and elevation change across the delta between March 1998 and May 1999 indicates patterns that partially support our conceptual model. As demonstrated at Lower Mandeville Tip, Donlon, and Venice Cut islands, tule marsh vegetation establishes quickly at intertidal elevations. However, subsequent colonization expansion is slow with an estimated maximum rate of 1.5 to 3 lineal m y^{-1}, as observed at Sherman Island. Where wave energy is high, marsh erosion may be increased further, as is evident over time at Lower Mandeville Tip. This is also consistent with observations of marsh erosion at other delta islands (e.g., Northwest Quimby Island) and with previous unpublished documentation of in-channel island marsh erosion.

Once vegetation has established, the rate of sediment accretion decreases but continues to contribute to maintenance or slow increase in marshplain elevation. All sites where feldspar marker horizons were recovered show at least 10 mm, and sometimes >20 mm of accretion during the ~13-month measurement period. More accretion occurred between March and August than between August and December. All sites in the central and western delta showed an increase in marshplain elevation (Sediment Erosion Table [SET] measurements) between June and August, which may

tributed to seasonal accumulation of belowground plant biomass. Sites with high rates of accretion rarely show similarly high rates of elevation change. Dating of shallow cores from the vegetation edges of our study sites using ^{210}Pb indicates comparable long-term rates—0.8–0.9 cm yr^{-1} (Browns, Sherman islands) and 1.1 cm yr^{-1} (Sand Mound Slough)—which are of similar magnitude to the accretion data. Although current rates of sediment accretion imply that recovering intertidal habitat prior to vegetation colonization is the rate-limiting step in tule marsh restoration, our exploratory coring of subtidal habitats at Mildred Island indicated that ~0.64 m of sediment had accumulated in the intervening 15 years since breaching of the levee at this extensively subsided island. If linear (obviously, an unlikely assumption given the SET and feldspar accretion data), this rate (4.3 cm yr^{-1}) suggests that return to high intertidal elevations will require at least a century or more.

Preliminary assessment of benthic macroinvertebrates and fallout insects in the delta's shallow-water habitats shows/suggests subtle differences among sites, habitat strata, and seasons. While nematodes and oligochaetes numerically dominate all benthic core invertebrates, the composition of crustaceans varied among amphipods (predominantly *Crangonyx floridanus*, *Hyallela azteca*, *Gammarus daiberi*), isopods (*Caecidotea racovitzae*) and cladocerans. Emergent insect (Chironomidae) larvae and pupae were well represented at a few sites (especially Venice Cut), and they appeared to be more dominant in shallow-water habitat created by dredge material disposal. In the central delta, we found the Upper Mandeville Tip reference site usually had the highest benthic macroinvertebrate density and Mildred Island the least. Macroinvertebrate assemblages in the emergent marsh habitat typically were less diverse than FAV habitats; amphipods and isopods were more prominent beneath FAV although most prominent amphipod species would be different depending upon FAV plant species and site. Collembolans and chironomids dominated the fallout insect numerical composition. No distinct trends in fallout insect densities occurred among sites or habitats, but taxa composition did appear to show differences between FAV (more collembolans, psychodids, and cicadellids) and emergent marsh habitats (more chironomids).

To date, 35 fish species (8 native and 27 introduced) have been collected at all study sites. Over 98% of the total fish collected are non-migratory residents. Migratory species collected included chinook salmon (native), striped bass (introduced) and American shad (introduced). Approximately 99% of the total catch (larval and juvenile fish) were introduced species. The density of all native fish species combined was significantly higher at Upper Mandeville Tip (reference site) compared with other breached levee study sites. The density of all introduced fish species combined was significantly different among study sites. These preliminary results suggest that historical ecological functions of the reference site provide essential habitat features for native fish. Our preliminary results also show that fish distribution and occurrence is influenced by physical habitat attributes, specifically, water temperature and SAV or FAV. Native fish spawned and reared during a constricted temporal window in the early spring months under a cool temperature regime, ranging between 10° and 18°C. In contrast, introduced fish spawned and reared from late spring into the early fall when temperatures were warmer, ranging between 15° and 25°C. Densities of various fish larvae were significantly different between inshore habitats vegetated by aquatic plants and offshore–open water habitats. Juvenile fish densities were also significantly different between aquatic vegetation and open water habitats.

Food web linkages between shallow-water habitat invertebrates and fish indicated that both emergent and aquatic vegetation habitats potentially contributed to prey resources of important fishes with open-water prey entering into the diets of more planktivorous fishes at some sites during the spring. For example, juvenile chinook salmon fed predominantly on chironomid larvae and pupae (more typical of emergent marsh) as well as the amphipod *Hyallela azteca*. California silverside appeared to reflect the predominant shallow-water habitat, preying upon planktonic cladocerans (*Daphnia* sp., *Simocephalus expinosus*, *Ceriodaphnia* sp.) associated with aquatic vegetation in extensively flooded islands like Mildred Island in April but incorporating more emergent marsh macroinvertebrates (chironomid larvae/pupae, ostracods) at the Upper and Lower Mandeville Tip sites. Seasonal differences were apparent, as silverside at Mildred Island had switched to emergent marsh chironomid larvae/pupae and fallout insects (collembolans, homopterans, Araneae) in July. Both splittail and tule perch displayed diet spectra of open-water, aquatic vegetation and emergent marsh prey, including cladocerans, amphipods (*Hyalella azteca*), and chironomid larvae and pupae. Bluegill illustrated extraordinary diet diversity from all habitats, regardless of the site—indicative of a completely opportunistic feeder. We also conducted field examinations of piscivorous largemouth bass, white catfish, and striped bass and found their gut contents to include several juvenile fish, including splittail (native), threadfin shad (introduced) and inland silverside (introduced).

Because of the prominence of the introduced FAV, water hyacinth (*Eichhornia crassipes*), in the delta, we focused particular attention on food web linkages between invertebrate prey associated with water hyacinth and the native aquatic FAV, pennywort (*Hydrocotyle umbellata*). Native to Brazil, water hyacinth was introduced into the delta region in the 1940s. Both types of FAV are common to shallow-water areas of the central delta, although the Department of Boating and Waterways controls water hyacinth with chemical spraying of 2, 4-D. We predicted that macroinvertebrate taxa richness and density would be different between the two vegetation types because of distinct physical and biological characteristics of the FAV canopies. Preliminary results show that both FAV types have diverse invertebrate assemblages in their root masses, dominated by amphipods. Fish diet analyses show that these amphipods provide food for fish caught in close proximity. Dissolved oxygen levels show a marked decrease underneath water hyacinth compared with underneath pennywort and adjacent to emergent vegetation.

These preliminary results provide some intriguing interpretations to the intent and process of restoring delta wetlands by breaching levees:

- The process of rebuilding intertidal elevations, which will be readily colonized by emergent marsh vegetation, cannot be directly extrapolated from what we know about the historical formation of the delta, and it depends greatly on the extent of leveed-island subsidence and the geomorphic region of the delta. On the basis of our independent estimates from feldspar, SET, ^{210}Pb and core stratigraphy, we suggest rates of ~4 cm yr^{-1} for subtidal habitats and ~1 cm yr^{-1} for intertidal habitats, depending to a large degree on the extent of wave and current energy. Intervention through enhanced sediment input (dredge material disposal) offers one of the few mechanisms of shortening the subtidal/FAV habitat phase.
- Native tule marsh vegetation will rapidly colonize emerging intertidal elevations but submerged and floating aquatic vegetation, including introduced species such as water hyacinth and *Egeria densa*, will dominate subtidal habitats; we are uncertain what the role of aquatic vegetation is in affecting the process of transcending from subtidal to intertidal elevations.
- The occurrence and density of introduced fishes likely will continue to exceed native fishes even with increased levee-breach restoration owing to the extensive area and duration of the subtidal-SAV/FAV phase of the restoration process and the ability of introduced fishes to exploit these habitats for a greater proportion of the year. The preponderance of native fishes appears during the winter and early spring, when water temperatures are at their lowest.
- Maximum invertebrate density typically occurs at the reference site, suggesting the mature site may be more productive; because composition of benthic macroinvertebrate and fallout insect assemblages in breached-dike, shallow-water habitats is generally similar to that for reference sites, breached-dike restoration sites should rapidly contribute to the delta's emergent wetland secondary production.
- Our preliminary findings—that emergent marsh and SAV/FAV habitats demonstrate distinct differences in terms of benthic macroinvertebrate and insect contributions—suggest ecological "trade-offs" to restoration strategies that promote large areas and long periods of the subtidal habitat phase of restoration.
- Evidence that food webs supporting both native and introduced fishes derive from SAV/FAV as well as emergent marsh habitats imply that, although SAV/FAV (including exotic species) habitats support prey resources of many fishes, more opportunistic fishes would benefit from early restoration phases, while more restricted habitat/food web specialists will benefit from later stages of predominantly intertidal habitats.

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INTRODUCTION

In our research under California Federal (CALFED) Bay–Delta Program's Category III, we conducted interdisciplinary investigations on historically breached dike wetlands in the Sacramento–San Joaquin Delta (delta) during 1997–99. Breaching of levees is among the many restoration approaches being considered to restore some integrity to the historical delta wetlands that have been "reclaimed" for agriculture by the construction of levees. However, similar to extant coastal restoration, we know little about the patterns, rates, and even endpoints of breached-levee restoration in the delta. A high degree of uncertainty and unpredictability continues to be associated with reestablishing sustainable ecological functions in restored wetlands: (1) direct measurement of function is difficult, if not impossible; (2) indirect or surrogate indicators have not be developed or validated; and (3) the diverse factors that promote rapid development of functions are unknown. Given the extensive changes in watershed structure and processes, complex management and manipulation of water, introductions of pollutants and nonindigenous species, and drastic declines in fish populations, there are many questions about the feasibility and practicality of restoration.

The intent of this project was to provide critical information necessary to predict whether breached-dike restoration strategies proposed under the CALFED program would provide natural wetland functions to support rearing habitat for endangered fishes such as juvenile spring-run chinook (*Oncorhynchus tshawytscha*) salmon and delta smelt (*Hypomesus transpacificus* McAllister) as well as habitat for other aquatic and terrestrial species. Our goals were as follows:

- Systematically address the present status, rates, and patterns of historical delta wetland restoration.
- Evaluate factors that have promoted rapid restoration of important wetland functions and factors that have potentially inhibited natural rates and patterns of functional development.
- Recommend optimum strategies and spatial distribution of future restoration initiatives.

Our interdisciplinary team combined the ecological expertise of the Univ. Washington School of Fisheries' Wetland Ecosystem Team (WET) with that of coastal marsh sedimentologists and geomorphologists from the University of New Orleans (UNO), and estuarine hydrologists and restoration planners from Philip Williams and Associates, Ltd. (PWA), in collaboration with the State of California Interagency Ecologic Program's (through the Department of Water Resources [CDWR]) monitoring of fish assemblages in the delta.

Approach and Objectives

Our fundamental approach was to use the different age distribution of selected breached-levee sites in a "space-for-time substitution" to predict the patterns and rates (trajectories) of restoration that would be expected from levee breaching (Fig. 1). We investigated historically restored and remnant natural wetland sites in the delta to determine their progress along important functional equivalency trajectories (Simenstad and Thom 1996). Over 2 years, we systematically evaluated the rates and patterns of restoration and determined sources of variability in naturally and artificially restored diked wetland sites from a broad spectrum of ages compared with the reference sites.

Our objectives were as follows:

- Assess indicators of hydrology, geomorphology, biogeochemistry, and ecology at diverse, differently aged

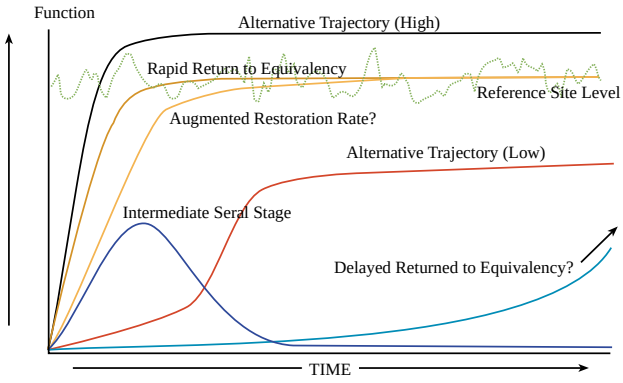

FIGURE 1. Alternative *functional equivalency trajectories* of ecosystem function with time since restoration. Time, rate and endpoint of alternative trajectories may not be predictable in the early stages of restoration.

sites of formerly diked wetlands that have reverted to tidal inundation.

- Compare indices of fish and wildlife habitat quality of these naturally breached-dike sites with existing mitigation and restoration sites purposefully constructed by dike breaching or comparable restoration actions.
- Using the same indicators, compare the status of these restored wetlands with wetland function at natural reference marsh sites.

A leading issue in restoration ecology is, or at least should be, whether ecosystems can be restored to their preexisting state. Given our modifications and manipulations of fundamental ecosystem-scale processes, such as hydrology and the introduction of non-indigenous species, in many systems there are equally viable possibilities for new trajectories and alternative ("steady state") ecosystems that may be less desirable endpoints of restoration. Restoration, which requires preservation of natural ecosystem dynamics, is fundamentally different from rehabilitation and reallocation, which are the consequences of strong human intervention (Aronson and Le Floc'h 1996). Through our study, we sought to determine (1) whether natural ecosystem processes and structure in the delta can sufficiently restore valued ecosystem functions such as provision of fish and wildlife habitat, (2) whether some processes such as sediment accretion can be artificially augmented, or (3) whether alternative ecosystems are likely unavoidable.

Study Design

On the basis of existing information (e.g., Atwater 1980) about the variation in wetland structure in the delta, we distributed our research sites among three distinct geomorphic settings: (1) northern wetlands including contiguous alluvial flood basins of the ancestral Sacramento River; (2) western tidal (fresh to brackish) wetlands; and, (3) east/south central wetlands along tidal distributaries of the ancestral San Joaquin River blind sloughs (Fig. 2). We chose six breached-levee sites (Table 1) to represent a spectrum of age between 13 and 67 years since restoration to tidal inundation with associated subsidence of approximately 1.1 and 2.3 m, respectively. For comparison, we selected four reference sites to represent remnants of the delta wetlands that have never been completely leveed. Breached-levee sites ranged from extensive open-water habitats that are primarily subtidal, such as Mildred Island (Fig. 3), to sites with both natural and artificially enhanced (e.g., by dredge material disposal) intertidal, emergent wetland development, such as Donlon Island (Fig. 4) and Venice Cut Island (Fig. 5). Many breached-levee islands show intermediate development of emergent wetland, such as Old Prospect Island (Fig. 6). Reference sites included delta wetlands that are known or appear to have not been successfully leveed and that have some prior geomorphic and ecological information, such as Browns Island (Fig. 7) and Lindsey Slough Island (Fig. 8). While often altered and severely reduced in size, such as Lindsey Slough Island, these sites are characterized by mature marsh communities that have persisted in the face of the delta's large-scale changes.

Methods

We assessed indicators of wetland status and restoration patterns and rates at all or subsets (e.g., fish sampling only being conducted in east/central delta sites) of the 10 sites in four primary habitat strata: (1) marshplain, (2) emergent macrophyte shoreline margin, (3) submergent macrophyte, and (4) open water unvegetated. Our proposed indicators of wetland status included the following:

- Geomorphology: GIS analysis of aerial photographs
- Marshplain development: Marsh surface sediment accretion rates and elevation changes
- Marsh vegetation complexity and structure: GIS analysis of aerial photographs; in situ groundtruthing along marshplain and shoreline transects
- Tidal elevations: in August 1998, we conducted an intense, high-resolution survey of benchmarks we installed at different study sites and vegetation assemblage transects using a real-time differential Global Positioning System (GPS; Trimble 4800) referenced to a grid of recently surveyed USGS benchmarks in

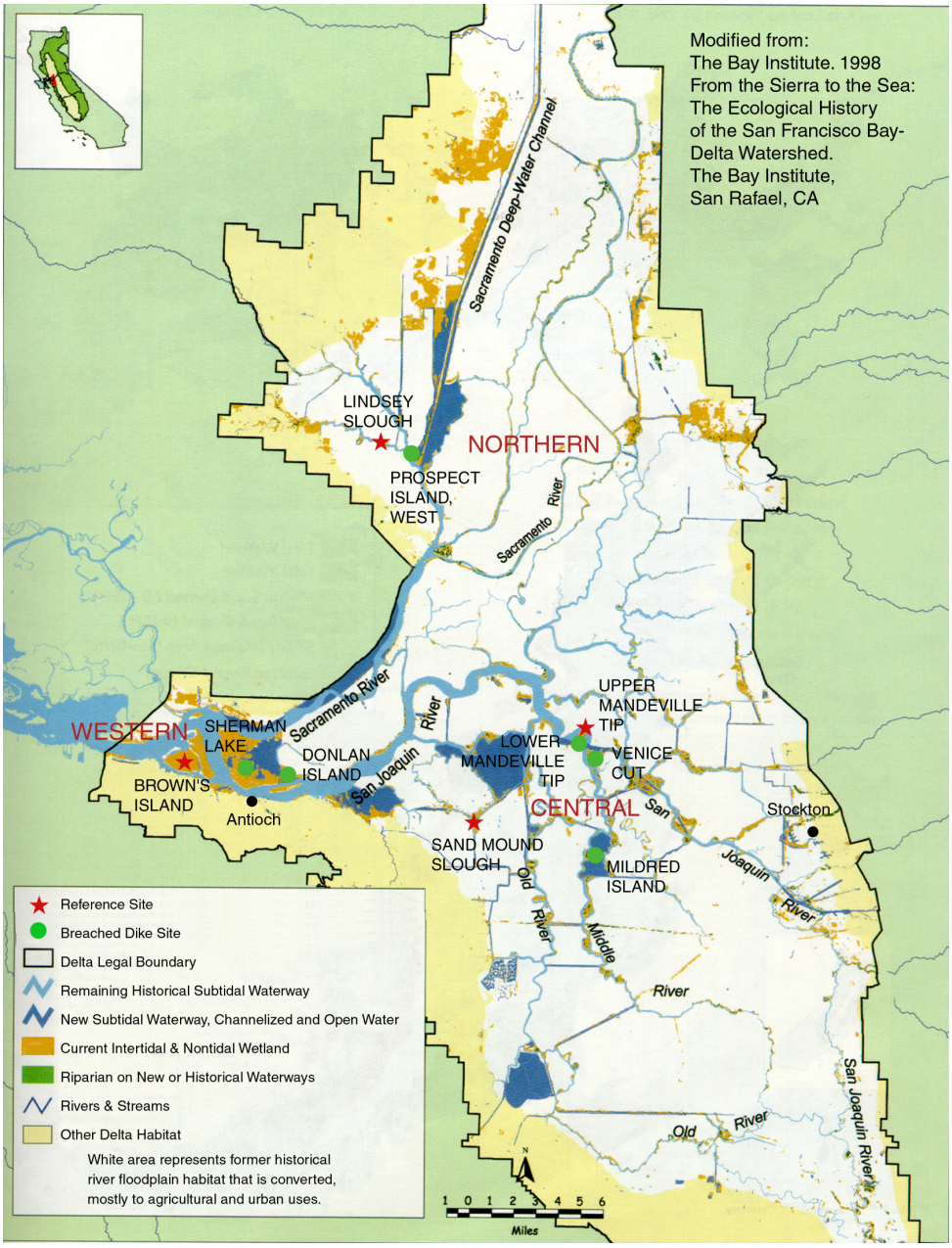

FIGURE 2. Present Sacramento/San Joaquin Delta configuration, indicating general study regions and sites (see Table 1 for details about sites).

the delta. The elevation of SET installations were also surveyed at the same time.

- Benthic and epibenthic invertebrate populations: 0.0024-m^2, 10-cm-deep benthic cores; 0.21-m^2 insect fallout traps; 0.5-m-dia., 333-mm zooplankton net vertical hauls and 1-m^2 horizontal tows (sample from fish egg and larvae samples); epibenthos on aquatic plant roots
- Fish assemblage and life history structure and behavior:
  - shallow shoreline areas with emergent vegetation: 15-m x 1.5-m, 3.1-mm mesh beach seine depletion; sampling in 15- and 30-m enclosures
  - shallow subtidal 1–3 m deep: 30-m x 3-m, 3.1-mm mesh purse seines
  - all habitat types: variable mesh (1.3-, 1.9-, 2.5-, 3.2-, and 3.8-cm) 15-m x 2-m gillnets, 30-min sets; fish egg and larvae net tows (variable distance/volume) with 1-m^2 opening, 2.5-m net)

TABLE 1. Breached-levee restoration (numbered) and reference sites (lettered and italicized) distributed among three geomorphic settings in the Sacramento–San Joaquin Delta; ages in parentheses refer to number of years since creation of dredged material islands or other restoration actions.

Sites	Area (ha)	Estimated subsidence (m)	Years breached
Northern wetlands			
1. Old Prospect Island	93	1.5	35?
A. *Lindsey Slough Island*	8–12		
Western wetlands			
2. Lower Sherman Island	1,327	2.3	73?
3. Donlan Island	95	2.0	61(13)
B. *Browns Island*	179		
East/central wetlands/sloughs			
4. Lower Mandeville Tip	30	1.1	65?
5. Venice Cut Island	83	2.0	67(14)
6. Mildred Island	406	4.5	15
C. *Upper Mandeville Tip*	36–41		
D. *Sand Mound Slough islands*	57–61		

FIGURE 3. Aerial view (1997) of Mildred Island, a deeply subsided site (approximately 5 m below MHHW) when the levee breached in 1983. The limited perimeter vegetation established 10 years following breaching but most of the site remains in open water.

- Food web linkages: systematic fish diet analyses, generating Index of Relative Importance (IRI) data
- Non-indigenous plant, invertebrate and fish effects: comparison of fish use and trophic interactions between exotic hyacinth and indigenous pennywort and parrots feather (*Myriophyllum aquaticum*) communities: resident fish diet (IRI), prey resource availability (benthic, epibenthic; invertebrate sampling), structural (root biomass, surface) and water quality (dissolved oxygen) comparisons

Geomorphological, sedimentological, and vegetation sampling are focused in emergent marsh strata, while most

FIGURE 4. Aerial view (1997) of Donlon Island, which has been fully tidal since 1937. Nine dredged material islands were created at Donlon Island in 1985 as part of a beneficial re-use effort. Initial colonization of bare soil occurred rapidly for approximately the first two to three years, then slowed or stopped (USFWS and USACE 1990).

FIGURE 5. Aerial view (1997) of Venice Cut Island, which had subsided 2 m after levees were built in 1906. The levee was breached during the construction of the Stockton Ship Canal in approximately 1933. Dredged material islands were deposited in 1986.

FIGURE 6. Aerial view (1997) of Prospect Island (West), which was inundated approximately 35 years ago.

FIGURE 7. Aerial photograph (1997) of Browns Island, the largest remaining natural tidal marsh in the Delta and the only site with an extensive branching channel network typical of the historical western delta. Browns Island is only slightly brackish, but it provides one of the best analogues of the delta's historically vast freshwater tidal marshes.

ecological sampling is focused at the interface and adjacent (open water) habitats. Sampling was concentrated in February–December 1998 with additional sampling in winter 1999. Frequency varies by study component and season: chronoseries of geomorphic and vegetation change include 1937–39, 1957, 1963–64, 1972, 1984–85, 1987, and 1997; sediment accretion occurs seasonally; juvenile fish are generally sampled monthly during both neap tide series, March-August, and during one neap tide series September-December, and fish egg and larvae March-August; invertebrate sampling is scheduled to occur monthly April-September. An intense period of vegetation groundtruthing, marsh and channel tidal elevation measurements, and coring for dating and contaminant samples occurred in August 1998.

Indicators of restoration patterns and rates included the following:

- Sediment accretion rate and structural changes: seasonal Sediment Erosion Table and artificial horizon measurements; ^{210}Pb and ^{137}Cs dating of marsh sediment/peat cores;
- development of tidal channel geomorphology: GIS-based comparison of aerial photograph chronoseries;
- change in marsh vegetation assemblage structure and zonation: GIS-based comparison of aerial photograph chronoseries;
- change in benthic invertebrate species diversity and assemblage structure, and age and trophic structure: analysis of invertebrate community and population structure; and
- fish age structure and consumption, autochthonous/allochthonous food web linkages: analysis of fish community structure and food web associations with invertebrate prey resources.

FIGURE 8. Aerial view (1997) of Lindsey Slough, in the northern delta.

Products

The following products are being generated between fall 1998 and winter 2000:

- Inventory and database of all naturally and artificially breached-levee sites in the delta;
- images (GIS maps, digital computer files) documenting geomorphic and other (e.g., vegetation) changes at ~12–15 sites since ca. 1930;
- wetland community analysis of structural changes over time compared with natural variation at reference sites;
- results from sampling and analyzing selected indicators of marsh functions and restoration patterns and rates at both breached dike and reference sites; and
- synthesis report and scientific journal publications describing patterns and rates of estuarine habitat function, factors controlling the probability and time to functional equivalency, and recommendations to CALFED for dike-breach criteria as part of an ecosystem-scale restoration strategy in the delta.

The following section describes our conceptual model of the sequence and mechanisms that we believe determines the evolution of freshwater tidal wetland evolution. Subsequent sections provide supportive information based on our field data that provides a test of this conceptual model and its implications, including indicators of sedimentary processes and a variety of ecological attributes.

CONCEPTUAL MODEL OF THE EVOLUTION OF FRESHWATER TIDAL WETLAND IN BREACHED-LEVEE SITES

Introduction

Sites available for restoration in the Sacramento–San Joaquin Delta typically are leveed and deeply subsided, up to 6 m below mean sea level. One method of restoring such sites is to breach the levee and restore tidal action. A deeply subsided breached site will initially be open-water habitat, perhaps with a fringe of emergent vegetation along the levee edge. Relatively little is known, however, about the long-term fate of such a site and whether it will remain open-water or evolve into tidal marsh. Whether deeply subsided breached sites evolve into tidal wetland and, if so, how quickly depend on the rate of sediment and biomass accretion relative to local sea-level rise.

The purpose of this component of the BREACH study was to develop a conceptual model of how freshwater tidal wetlands evolve in breached-levee sites of the Sacramento–San Joaquin Delta. In particular, the conceptual model addresses rates and patterns of accretion and of emergent vegetation establishment on accreted surfaces.

On a related point, this component of the study also includes a characterization of tidal marsh morphological features, including tidal channels, marshplains, and natural levees. We developed the conceptual model and characterization of marsh features with the intention that they be applied in planning future efforts to restore delta tidal wetland.

Hydrogeomorphic Setting of the Delta

The Natural Delta

The delta's freshwater tidal marshes were formed over the past 6,000 years by sea-level transgression. Slowly rising sea levels submerged what is now the San Francisco Bay Estuary (Fig. 9). In the delta, the rise in sea level (~1-2 mm yr^{-1}) was balanced by vertical marsh growth through peat formation and sedimentation (Atwater et al. 1979), creating extensive freshwater tidal marshes (Fig. 10). The marshplains were predominantly vegetated by bulrush (*Scirpus* sp.), cattails (*Typha* sp.), and common reed (*Phragmite* sp.), collectively known as "tule." As a rising sea expanded landward into the Central Valley, tidal waters overwhelmed and backed up the outflow of the major rivers, drowning former floodplains and uplands, and converting them to extensive freshwater–tidal marsh. These marshes were drained by an intricate tidal drainage system whose major sloughs merged upstream into the distributary channels of the main river.

In the natural delta, marshplain elevations kept pace with

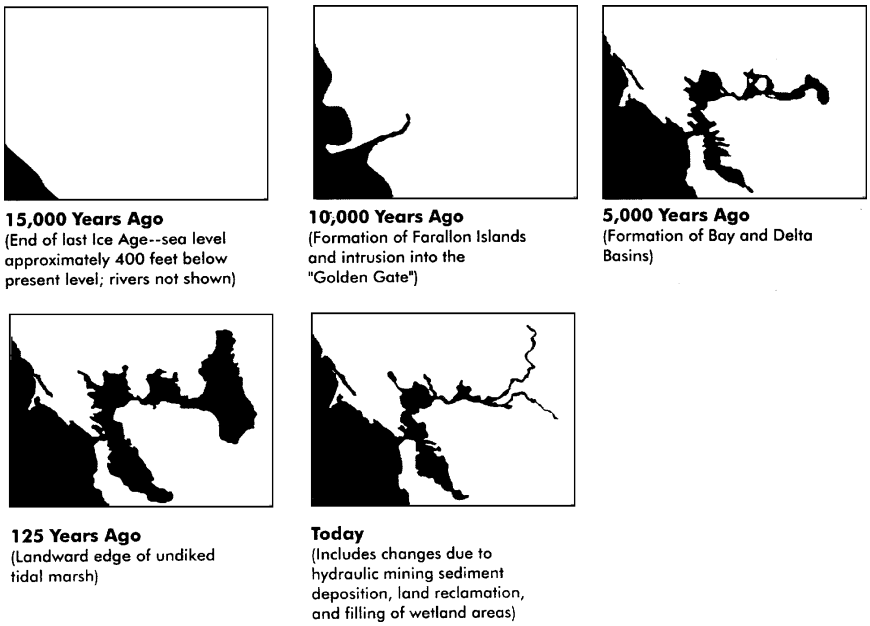

FIGURE 9. The invading estuary. Sequential sea level rise created the bay–delta we know today. Source: San Francisco Estuary Project, adapted from Atwater 1979 and Atwater et al. 1979 as reproduced in TBI 1998.

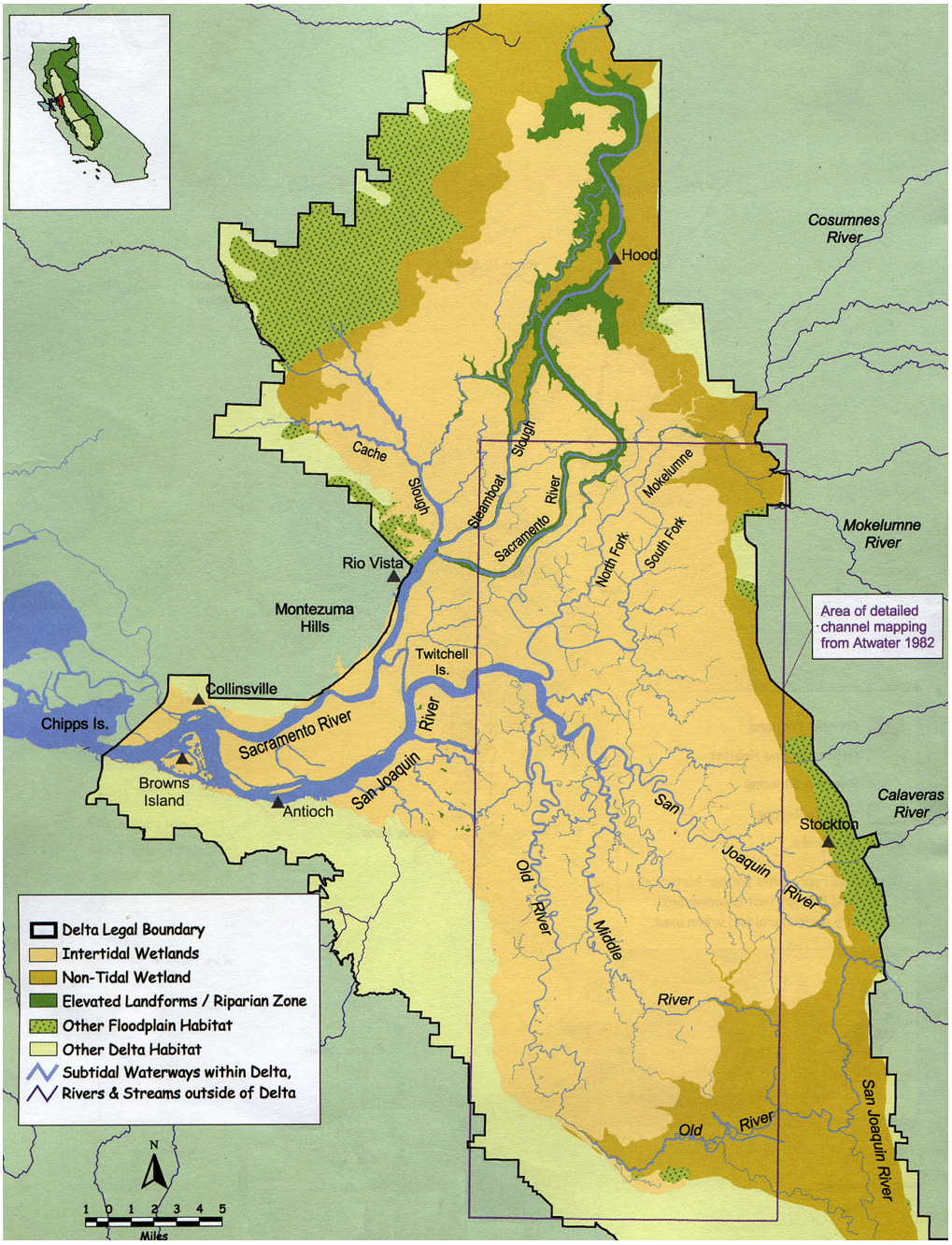

Figure 10. Historical tidal wetlands of the Sacramento–San Joaquin River Delta.

rising sea level at approximately the MHHW elevation (Atwater 1980), building up peat and peaty mud through sediment deposition and biomass accumulation. The deepest of these deposits have reached a thickness of ~15–18 m at Sherman Island (Atwater 1982; CDWR 1995).

The area we now refer to as the "delta" was actually shaped from two former distinct river deltas created by the Sacramento and San Joaquin rivers (Fig. 2). Most freshwater flow and sediment delivered to the estuary originated in the Sacramento River watershed. During large flood flows, silts and sands would be deposited adjacent to the river channel, forming natural levees above the marshplain. These natural levees were highest in the upstream reaches, supporting tall riparian vegetation, and disappeared into the marshplain near the confluence of the Sacramento and San Joaquin rivers. As sea level rose, these levees were increasingly prone to breaching during major flood events, creating alternative flood channels for the Sacramento River. This process eventually led to

the formation of a series of branching distributary channels with natural levees at the mouth of the Sacramento River, resulting in a distinct "crow's foot" delta (Fig. 10). The main distributaries of the Sacramento River are the mainstem of the Sacramento River, Steamboat Slough, Sutter Slough, Elk Slough, and Georgiana Slough (Atwater 1982). The distributaries of the Sacramento Delta were surrounded by tidal backwater areas to the west (Cache Slough) and east (Mokelumne River sloughs). Cache Slough drained and fed an extensive tidal tule marsh and also carried Sacramento River floodwater from the Yolo Basin further upstream.

In contrast, flood flows of the San Joaquin River were smaller, carrying and depositing less sediment than Sacramento River flows. As a result, natural levees were less well defined along the lower San Joaquin, supporting willow, fern, and shrub vegetation (Atwater and Belknap 1980). The lower San Joaquin River supported an extensive floodplain tule marsh with many small branching distributary channels (Atwater and Belknap 1980), a landform that merged with tidal tule marsh around the latitude of Stockton. The main channel of the San Joaquin divided in this region into three major distributary channels meandering through the tidal tule marsh: Old River, Middle River, and the mainstem San Joaquin River. Marshplains of the San Joaquin Delta received frequent tidal inundation and sustained a fully developed tidal slough system, a feature not so apparent in marshes closer to the Sacramento River Delta.

Much of the delta was historically freshwater, with occasional saline intrusions during periods of low river flow. The Montezuma Hills usually marked the farthest upstream intrusion of sea water with the exception of low flows during the late summer and early autumn, when brackish water (~2 ppt) could be found in the western delta (Atwater and Belknap 1980). Pollen analysis of cores in the far western delta (Browns Island) by May (1999) indicates alternating periods of high and low salinity in this location over the past 2000 years as evidenced by changes in salinity-tolerant plant species. During the past ~70 years, saline conditions have shifted to their highest levels over the 2000-year record. The timing of the shift suggests that upstream water diversions played an important role in this shift. However, the pollen record indicates that the shift to more saline conditions has partially reversed during the last 2 decades. Spring freshwater flows appear to be particularly important in determining the type of marsh vegetation that establishes in a given year.

Human Intervention in the Delta

The natural landscape of the delta has been highly altered by human activity since the arrival of gold miners around 1849. Land reclamation, primarily for agriculture, has resulted in the loss of ~97% of the delta's original tidal wetlands (calculation based on Atwater and Belknap 1980 and San Francisco Estuary Project 1991). The original natural marshes are represented today by relict delta wetlands such as Browns Island and narrow bands of emergent vegetation located between channels and constructed levees (Fig. 7). Reclamation eliminated virtually all but the largest of the tidal channels. The remaining natural channels were artificially connected together by constructed channel segments. The result was the creation of a series of leveed islands separated by through-flowing channels.

Drainage of the wetlands—accomplished through levee-building, ditching, and draining—has resulted in high rates of subsidence, with some areas of the delta up to 6 m below mean sea level. Subsidence occurs through direct dewatering of the substrate and enhanced aerobic decomposition of organic material in marsh soils.

Sediment supply to the delta has been highly modified by upstream activities. Hydraulic mining in the mid- to late-1800s washed tons of sediment into Central Valley rivers, sediment that is still being washed into the delta today. Leveeing upstream rivers removed the natural river floodplains as sediment sinks, further increasing sediment supply to the delta. These effects on sediment supply are partially offset by the sediment trapping effect of numerous upstream dams and armoring of upstream river banks, which limits bank erosion as a sediment source. Human-induced hydrologic changes have also affected sediment inflow. Overall, sediment supply to the delta appears to be higher at present than under natural conditions (Philip Williams & Associates [PWA], unpublished).

Conceptual Model of Breached Site Evolution

The pattern of evolution of natural tidal marshes that sustained extensive vegetated marsh plains and tidal slough systems over the last 6000 years cannot necessarily be extrapolated to how subsided breached sites will evolve. These natural marshes were formed by the gradual upward and landward expansion of existing marshes, keeping pace with sea level rise. In contrast, the establishment of vegetated marsh in subsided sites—which account for almost all potential restoration sites—requires the rapid accumulation of sediment until ground elevations are high enough for vegetation colonization. Such an accumulation is greatly affected by physical processes and is not a foregone conclusion. This section provides our concep-

tual model of tidal wetland evolution in deeply-subsided, breached sites.

Marsh Elevation Growth

The primary determinant of whether a sustainable vegetated marsh will form on a subsided breached site is whether accumulation of material relative to sea level will build up ground elevations high enough for emergent vegetation colonization. Elevation gain relative to sea level in any given time period is a function of accumulation, erosion, subsidence, and sea level rise.

- Accumulation in subsided restored sites is mainly dependent on the following factors:
  - Bed material accumulation. Sand and gravel bed materials settle quickly in the low energy environment of a breached site. Bed material accumulation occurs only when breach site elevations are below adjacent channel bottom elevations.
  - Suspended sediment concentrations in the water column. These concentrations are in turn influenced by extent of fluvial sediment inputs, proximity to intertidal mudflats or shallows, and depth of the water column.
  - Settling velocities of suspended sediments. For the silts and clays that dominate suspended sediments in the Estuary, the main factor affecting settling velocities is flocculation, which significantly increases settling velocity. This occurs anywhere salinities are greater than about 1ppt (mainly San Francisco Bay with seasonal salinity intrusions into the west delta).
  - Depth and period of tidal inundation. As ground surfaces rise, they are inundated less deeply and less frequently, reducing net sedimentation rates.
  - Organic biomass accumulation. This can occur from different sources where there are anoxic conditions, such as subtidal detritus from submerged aquatic vegetation or emergent vegetation root mass. Biomass is an important component of accumulation in the delta's natural wetlands, particularly in the south-central delta, where soil organic content is typically 50-70%. In the northern and southernmost parts of the delta, soil organic content diminishes to 5-10% (Atwater and Belknap 1980).
- Erosion of sediments is dependent on the following:
  - Exposure to wind wave action. Scouring due to wave action for a given wind climate is dependant mainly on water depth and wind fetch.[1]
  - Tidal currents. These tend to be quite small except where tidal sloughs are forming.
  - Wind and density driven currents. These also tend to be quite low intensity, but sufficient to move submerged organic detritus.
  - Size and cohesiveness of sediments. For non-cohesive sediments, larger sediments are generally more resistant to erosion than smaller ones. Cohesive sediments bond with the bed once deposited, with the cohesive strength determined mainly by the length of time sediments have been deposited.
  - Subsidence in restored sites is mainly due to autocompaction, which tends to increase with the proportion of organic accumulation and with elevation. In certain areas, groundwater extraction and gas field pumping can contribute to local and regional subsidence.
  - Sea level rise is a function of regional geologic uplift and eustatic (global) sea level rise. In the time frame of restoration, sea level is predominantly determined by eustatic sea level, driven by ocean thermal expansion and glacial melting in response to global warming.

Evolutionary Trajectories and Endpoints

In general there is a tendency for accumulation processes to decline and for erosive processes to increase as elevations increase. This means that there will be a tendency for these processes to equilibrate at a particular elevation and that subsided breached sites can follow one of three evolutionary trajectories:

1. **Deepening open water.** Here accumulation does not keep pace with sea level rise, erosion, and subsidence. The site gets deeper over time creating permanent subtidal habitat.
2. **Open water equilibrium.** Here accumulation initially occurs faster than erosion, sea level rise, and subsidence. However, accumulation rates decline as elevations increase and an equilibrium occurs below the elevation where emergent vegetation can colonize. With this scenario, the site becomes permanent open water habitat, whose elevations keep pace with rising sea level.
3. **Vegetated tidal marsh equilibrium.** Here accumulation occurs to raise ground elevations high enough for emergent vegetation colonization. Once plants are established, they can expand laterally into lower elevation zones. In addition, the presence of vegetation reduces erosive processes and increases in-situ bioaccumulation. However, as marsh plain elevations increase, accumulation rates decline and eventually

[1]Fetch is the distance of open water over which wind blows, creating waves.

an equilibrium elevation is reached—typically within approximately 0.2 m of the diurnal high tide (MHHW) (Atwater 1980).

Vegetation establishment is a critical stage in site evolution because vegetation greatly reduces the potential for scour, tends to promote additional sedimentation, and contributes biomass. In the delta, emergent vegetation is believed to be the most significant type of vegetation in site evolution, although submerged aquatic vegetation may also play an important role. Emergent vegetation grows in the approximate intertidal range (see results for a more detailed discussion of vegetation elevations). Emergent vegetation colonization occurs in two ways: (1) pioneer colonization and (2) lateral expansion colonization. Pioneer colonization occurs by seed or deposition of vegetation fragments. Once vegetation becomes established, lateral expansion can extend lower in the tidal zone by extension of rhizomes.

Limitations on Evolution of Restored Vegetated Marshes

In San Francisco Bay, several breached-levee sites have evolved from open water to vegetated marsh (e.g., part of Muzzi marsh and Carl's marsh on the Petaluma River). However, sedimentation of silts and clays (mud) in the bay is more rapid than in the delta because of higher suspended sediment concentrations and because higher salinity levels enhance flocculation and settling rates. Breached-site evolution in the delta is more likely to follow the open water equilibrium trajectory. The deepening open water endpoint has not been observed in breached of artificially restored sites of the delta and is not expected to be significant in this system (assuming no significant changes in physical processes).

In open water sites at equilibrium, accumulation above the equilibrium level is limited by high rates of erosion. Sediments initially accumulate rapidly, while depths are well below the equilibrium elevation. As elevations increase and approach the equilibrium level, scour events become more frequent and more intense, transporting sediments from the site.

Based on available studies of analogous systems, wind-wave action appears to be the primary mechanism responsible for maintaining open water equilibrium in restored subsided sites. Unfortunately, there is no known research on open water equilibrium that applies directly to subsided breached-levee sites. There is, however, applicable literature on open water lagoons. Lagoons are similar to breached sites in that they are enclosed open water embayments subject to tidal action with sediment inflow, sediment storage, and internally-generated wind-waves. The majority of U.S. lagoons for which accretionary status has been summarized (Atlantic and Gulf coast lagoons) are in open water equilibrium with the equilibrium depth determined primarily by the depth of effective wind-wave action (Nichols and Boon 1994). Wind-wave action is a function of wind energy, fetch, and water depth. For the same wind and fetch conditions, the transport energy of waves increases with decreasing water depth (PWA 1999). Therefore, the tendency for wave transport of sediments increases with increasing accumulation.

Whether a site will become marsh or remain open water depends on fetch, wind energy, storm events, sediment characteristics, and other factors. For all but sites at the extreme ends of the spectrum (i.e., low-energy/high-sediment or high/energy/low-sediment sites), predicting the combination of these factors that is likely to result in one site fate versus the other is complex and poorly understood.

Methods

We collected historical data and conducted field studies at the 10 study sites to characterize open-water sedimentation rates, emergent vegetation elevations, rates and patterns of emergent marsh expansion over time, marshplain and natural levee elevations, and tidal channel hydraulic geometry.

Open Water Sedimentation Rates

An open-water core was collected at Mildred Island to estimate the rate of subtidal sedimentation. The ~1.1-m core was collected in 2.8 m of water on the western side of the site in August 1999. The depth of subtidal accumulation since the time of levee breaching (1983) was estimated as the distance between the top of ground and the agricultural field soil horizon. The core used an aluminum pipe 7.6-cm (3-in) in diameter. Because of equipment failure, additional cores could not be collected. Instead, seven depth probes were conducted in open-water areas to identify the depth to refusal at 104 kg (230 lbs) dead weight. Because pre-breach agricultural soil is often more resistant to probe penetration than overlying estuarine and alluvial deposits, depth to refusal can indicate depth of overlying deposits. Depth to refusal correlated very well with depth of post-breach deposition for the one successful core. A core was collected from one of the depth probes driven to refusal and found not to have penetrated the agricultural soil horizon, suggesting that depth to refusal does not overestimate, and may underestimate, depth of post-breach deposition.

Emergent Vegetation Elevations

As described earlier in the conceptual model discussion, the establishment of emergent vegetation is of particular geomorphic significance because it promotes more rapid vertical marsh growth. We collected emergent vegetation data for use in characterizing elevation distribution within the tidal zone. Spot elevations of the colonizing emergent edge were surveyed at Old Prospect West, Upper Mandeville Tip, Venice Cut, and Donlon islands. Because we were interested in learning about the lowest colonization elevations, the spot survey points were weighted toward the lowest elevation patches of emergent edge.[2]

Rates and Patterns of Emergent Marsh Expansion

We reviewed historical aerial photographs and other detailed vegetation mapping to track changes in emergent marsh area over time at Lower Mandeville Tip and Sherman islands. Time series of aerial photographs were reviewed for rates and patterns of marsh expansion and erosion. The photographs were scaled and then the marsh edge was traced. Aerial photograph analyses for additional sites (Venice Cut, Donlon, Old Prospect West, and Browns islands) are ongoing and will be presented in subsequent reports.

Marshplain and Natural Levee Elevations

We conducted high-resolution GPS surveys (see Introduction, page __) of marsh elevation transects at Lindsey, Old Prospect West, Browns, Sherman, Upper and Lower Mandeville Tip, and Sand Mound Slough islands. Transects for the reference sites—Lindsey, Browns, Upper Mandeville Tip, and Sand Mound islands—included survey of the historical channel edge to characterize remnant features of the natural levee. Vegetation data were collected along the transects for qualitative vegetation characterization.

We used two vertical datums for analysis: National Geodetic Vertical Datum (NGVD) and tidal datums (i.e., MHHW, MLLW, or MTL*). The NGVD is a vertical datum fixed at the mean sea level of 1929. It has the advantages of being in common use and being accurately available throughout the entire study area. Tidal datums vary locally and have the advantage of providing insight to geomorphic processes relative to tide levels. Unfortunately, use of tidal datums was based on limited information and, according to marshplain elevation data collected during the study, appears to have introduced inaccuracies, primarily in the north delta. We used published NOAA tidal benchmark information (National Geodetic Survey 1998) to characterize tide elevations by site (Table 2). For each site, we located the nearest NOAA station with tidal statistics referenced to a known vertical datum, usually NGVD. Often, no vertical datum was available for the nearest NOAA station (only tidal elevations relative to MLLW), so the conversion for the next nearest station was used. Local tide data referenced to NGVD were not available for Lindsey Slough, so the NGVD-MHHW conversion for Lindsey Slough was based on data for Rio Vista (Table 2), far from the site. For the north delta, elevations may have been underestimated by ~0.2 m when expressed relative to tidal datums.

Field surveys for this study used recently surveyed (1997; see Introduction, page __) elevation benchmarks available in NAVD88. The GPS field data were collected in NAVD88 and then converted to NGVD using site-specific latitude and longitude coordinates.

Tidal Channel Hydraulic Geometry

The term hydraulic geometry refers to empirical relationships between the shape of natural channels and "dominant discharge," or channel-forming flow. For tidal channels in mature marshes, the channel-forming flow is largely a function of the marsh area drained (i.e., watershed area) and the tidal range. Since the tidal range is relatively consistent throughout the delta (Table 2), we have used marsh area as the predictive variable for empirical correlation with channel dimensions.

Hydraulic geometry relationships were developed using recent and historical information. Recent relationships were developed for selected channel cross-sections at each study site with extensive channel formation: Browns, Sherman, and Lower Mandeville Tip. Channel cross-sections were surveyed in August 1998 using GPS or traditional rod and level surveys. Approximate drainage areas for each cross-section were measured using planimeter readings of aerial photographs and correlated with channel depth, width, and cross-section area. Drainage areas are approximate since available aerial photographs were not sufficiently detailed to show the small channels in the upper reaches of the tidal drainage network. Historical channel cross-sections for the San Joaquin River near the confluence with the Sacramento River were obtained from historical hydrographic mapping (USCGS 1867). Top widths for various historical tidal channels and historical

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[2]We collected additional vegetation data not presented in this report. For each elevation transect survey point, vegetation was classified by species and percent cover. These data are a source of vegetation frequency, elevation, and plan view distribution information.

*MHHW = mean higher high water; MTL = mean tide level; MLLW = mean lower low water.

TABLE 2. Tidal characteristics of BREACH study sites.

	Sites and Nearest Tide Station(s)				
	Browns, Sherman, Donlon	Lindsey, Old Prospect West	Upper and Lower Mandeville, and Venice Cut	Sand Mound Slough	Mildred
Tide Level	Antioch (#941 5064)	Ryer Island (#9415479) and Rio Vista (#941 5316)	Prisoners Point (#941 5149) and Potato Point (#941 5198)	Dutch Slough (#941 5053)	Wards Island (#941 5105) and Dutch Slough (#941 5053)
			Elevation (m MLLW)		
MHHW	1.17	1.26	1.03	1.03	1.20
MHW	1.02	NA	0.90	0.89	1.06
MTL	0.60	0.72	0.52	0.52	0.53
MLW	0.18	0.17	0.14	0.16	0.14
MLLW	0.00	0.00	0.00	0.00	0.00
			Elevation (m NGVD29)		
MHHW	0.87	1.07	0.83	0.91	1.09
MHW	0.73	NA	0.70	0.77	0.94
MTL	0.30	0.53	0.32	0.41	0.41
MLW	-0.12	-0.01	-0.06	0.04	0.02
MLLW	-0.30	-0.18	-0.20	-0.12	-0.12

MHHW = mean higher high water; MHW = mean high water; MTL = mean tide level; MLW = mean low water; MLLW = mean lower low water, NGVD = National Geodetic Vertical Datum (approx. 1929 mean sea level).

Note: Tide stations listed are the nearest for which tidal summary data (i.e., MHHW, MHW, MTL, MLW, MLLW) is available. Where two tide stations are listed, the first station was used for tidal datums relative to MLLW and the second stations was used to reference the MLLW elevation to NGVD because this data was not available for the first station.

drainage areas were estimated from geologic mapping showing the historical channels (Atwater 1982). Hydraulic geometry relationships for the San Francisco Bay, for which a larger database of hydraulic geometry relationships exists, are presented for comparison. The bay trend line incorporates data from 46 channel cross-sections in 7 natural tidal marshes (PWA, unpubl., modified from PWA et al. 1995).

Preliminary Results and Discussion

Open Water Sedimentation Rates

Core inspection indicates that 0.75–0.81 m of deposition has occurred on top of the original Mildred Island agricultural field horizon since the site was breached in 1983 (Table 3). This corresponds with an average sedimentation rate of 47–51 mm yr^{-1}. The resulting change in ground elevation may be lower due to compaction of the underlying soils. Depth to refusal, hypothesized to represent post-breach deposition (see discussion in preceding Methods), varied between 0.4–0.9 m and averaged 0.6 m. The data show no correlation between amount of wind shelter and sedimentation.

Open-water sedimentation rates at Mildred Island are consistent with elevation change rates available for Rhode Island. Recent (1999) hydrographic surveys at Rhode Island by the California Department of Fish and Game indicate that ground elevations are ~0.6 m (2 ft) below MLLW (T. Gardner, Cal. Dep. Fish & Game (CDFG), pers. comm.). A local farmer estimates pre-breach ground elevations at ~1.8 m (6 ft) below MLLW (T. Gardner, CDFG, pers. comm.). This amounts to a net elevation change of 44 mm yr^{-1} (0.14 ft yr^{-1}) relative to sea level since breaching in 1971.

The observed rates of subtidal sedimentation at Mildred Island and elevation change at Rhode Island represent the maximum accumulation rates expected during site evolution since sediment transport energy increases with ground elevation. In addition, a portion of the observed sedimentation represents an initial sediment pulse at breaching. During breaching, several non-recurring sources of sediment enter the site: the breached section of levee, soil scoured from immediately inside the breach, and possibly deposits scoured from the bottom of the exterior channel.

In contrast to the high rates of accumulation observed at Mildred and Rhode islands, it appears that sedimentation in many of the large, open-water areas in the delta may be limited by long fetches and high wave action. Large, open-water sites such as Sherman, Big Break, and Franks Tract have persisted over decades and may have reached an open-water equilibrium. If, for example, we assume that Franks Tract filled in at half the rate observed at Rhode Island

TABLE 3. Levee and marshplain elevations of the study sites and selected Atwater (1980) sites.

Hydrogeo-morphic region	Site	Type	Feature	Elevation (m) NGVD	Elevation (m) MHHW
Sacramento River Delta	Lindsey Slough (this study)	reference	average marsh plain	0.83	-0.24
	Lindsey Slough (Atwater 1980)	reference	average marsh plain	1.00	-0.07
	Lindsey Slough (this study)	reference	natural levee crest		
	Lindsey Slough (Atwater 1980)	reference	natural levee crest		
	Old Prospect West	*breached*	average marsh plain	*0.61*	*-0.46*
San Joaquin River Delta	Upper Mandeville	reference	average marsh plain	NA	NA
	Upper Mandeville	reference	natural levee crest		
	Sand Mound Slough (this study)	reference	average marsh plain	0.76	-0.15
	Sand Mound Slough (Atwater 1980)	reference	average marsh plain	0.80	-0.11
	14 mile slough channel island (Atwater 1980)	reference	average marsh plain	0.80	0.00
	Old River channel island (Atwater 1980)	reference	average marsh plain	0.90	0.03
	Middle River (Atwater 1980)	reference	natural levee crest	0.90	0.03
	Lower Mandeville	*breached*	average marsh plain	*0.25*	*-0.58*
West Delta	Browns (this study)	reference	average marsh plain	0.97	0.10
	Browns (Atwater 1980)	reference	average marsh plain	1.00	0.13
	Sherman (this study)	*breached*	average marsh plain	*0.49*	*-0.38*

(0.5*44 mm yr^{-1} = 22 mm yr^{-1} relative to sea level) and that Franks Tract was subsided to approximately 1.9 m below MLLW at the time it was breached in 1938,[4] we would predict that Franks Track would have filled to within millimeters of MLLW by now. Instead, most of the site remains more than 2 m below MLLW today (NOAA 1998).

Emergent Vegetation Elevations

Emergent edge surveyed for this study generally ranged between +0.2 to -0.6 m MLLW, ignoring high and low outliers, and had a median value of -0.3 m (Fig. 11). The colonizing edge surveyed in this study was spreading from established patches of emergent vegetation and thus represents lateral expansion rather than pioneer colonization. Vegetation patches surveyed were initially colonized 12–14 years ago (Donlon and Venice Cut) or longer (Old Prospect West and Upper Mandeville Tip).

Limited data from other delta surveys are available to characterize pioneer colonization elevations. Initial vegetation elevations following the placement of dredged material at Donlon and Venice Cut islands are available in post-project monitoring reports (U.S. Fish & Wildlife Service and U.S. Army Corps of Engineers 1990). Comparing the pioneer colonization data for Donlon and Venice Cut with our study data by age of site indicates that pioneer colonization generally occurs at higher elevations than lateral expansion (Figs. 12 and 13). Median values of pioneer and lateral expansion colonization are +1.0 and -0.3 m MLLW, respectively. Pioneer colonization occurs as low as 0.4 m and lateral expansion as low as -0.6 m MLLW (ignoring outliers). The level of uncertainty associated with elevations from the Donlon and Venice Cut post-project monitoring projects is significant (U.S. Army Corps of Engineers and U.S. Fish & Wildlife Service 1990). Survey results are accurate to within approximately ±0.08 m (±0.25 ft) and the methods used for vertical control are less accurate than those used in the current study. Results of future monitoring of pioneer colonizing vegetation should be used to confirm the elevations from Donlon and Venice Cut islands presented here.

[4]Based on an average subsidence rate of 74 mm/yr (CDWR 1980; p. A-1) over the ~33 years it was leveed. Assume subsidence occurs from an initial elevation equal to MHHW, 1.03 m above MLLW.

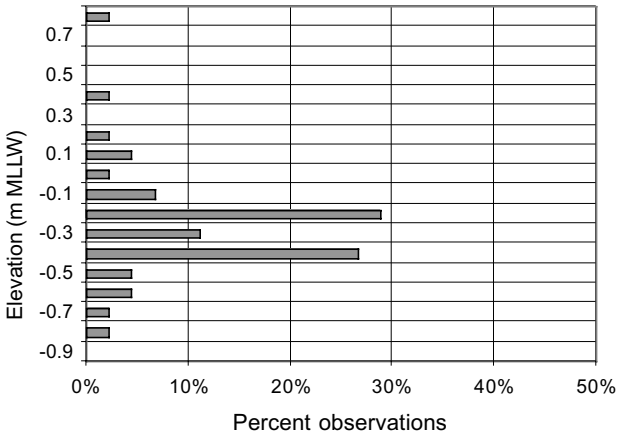

FIGURE 11. Percent occurance of elevations of colonizing emergent edge at Prospect West, Upper Mandeville, Venice Cut, and Donlon Islands. Source: Field surveys, August 1998 (this study). Note: Median = -0.3 m.

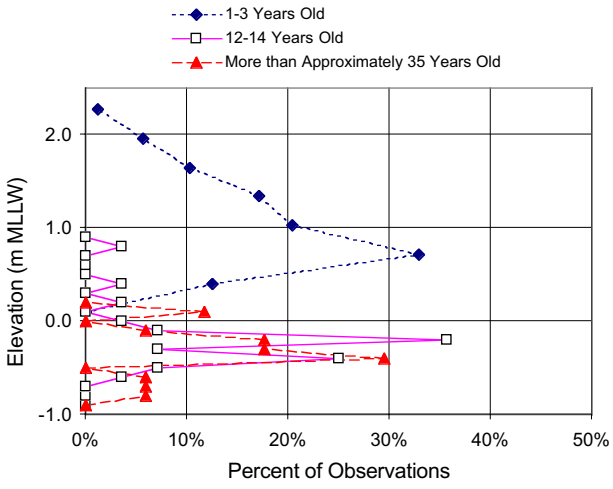

FIGURE 12. Percentage occurrence of elevations of colonizing emergent edge by age of vegetation. Note: Tide elevations for Prospect West may be too low. Source: Field surveys August 1998 and U.S. Army Corps of Engineers (USACE) and U.S. Fish & Wildlife Service (USFWS) (1990).

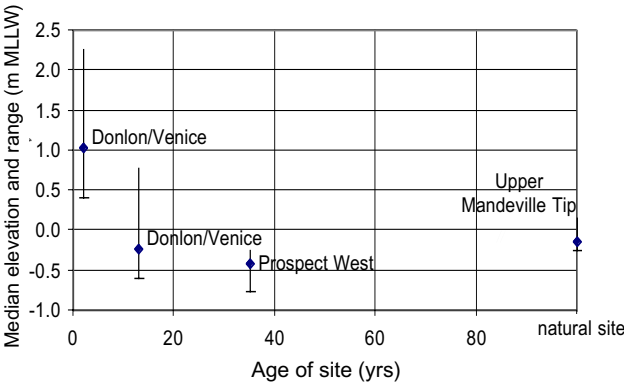

FIGURE 13. Median and range of elevations of colonizing emergent edge by age of vegetation. ide eleva-T tions for Prospect west may be too low. Source as for Fig. 12; abbreviations as for Table 3.

FIGURE 14. Lower Mandeville Tip provides an example of rapid revegetation at a shallowly subsided site following breaching. The majority of the site was at intertidal elevations when it breached in 1933. This aerial photograph, taken in 1937, shows nearly complete revegetation 4 years later. The photograph also shows significant erosion between 1937 and 1993 in the southern part of the site, where wave energy is high along the Stockton Deep Water Ship Channel.

Rates and Patterns of Emergent Marsh Expansion

The aerial photograph analysis indicates that initial vegetation colonization occurs and is followed by slow lateral expansion in only the most sheltered locations. Lower Mandeville Tip provides an example of rapid revegetation at a shallowly subsided site following breaching. A 1937 photograph of Lower Mandeville Tip shows nearly complete revegetation in the 4 years following introduction of tidal action (Fig. 14). Because the site was leveed for only a brief time, it was probably not deeply subsided when it breached. It appears that the site was at the appropriate elevation for rapid pioneer vegetation colonization. Comparison of the 1937 photograph with a 1993 photograph (Fig. 14) indicates significant erosion between 1937 and 1993 in the southern part of the site, where wave energy is high along the Stockton Deep Water Ship Channel. This erosion is consistent with previous informal documentation of marsh erosion of in-channel delta islands (Fox 1996).

The first available aerial photograph of Sherman Island (1937) was taken over a decade after the island breached, apparently after the period of initial colonization. Fifty-seven years of historical photographs for Sherman Island (1937–94) indicate that lateral vegetation expansion proceeded slowly in some of the most sheltered areas and not at all in the remainder of the site. In the southwestern part of the site, where bottom slopes are gentle and patches of existing marsh are most sheltered from wave action and tidal currents, the maximum expansion rates observed at selected vegetation patches were 1.5–3 m yr^{-1} (86–171 m in 57 years). If expansion were to continue at this maximum rate (an unlikely assumption), it would take several hundred to a thousand years for Sherman Island to become completely vegetated.

Marshplain and Natural Levee Elevations

Natural (Reference) Sites

Average marshplain elevations were close to MHHW, as expected (Table 4). With one exception, elevation plots of the reference site transects (Fig. 15) showed relatively flat marshplains. The ground surface for the Upper Mandeville Tip transect was highly irregular, presumably due to localized disturbance. The transect passed through a beaver dam and patchy areas of ponding and woody debris. At two of the sites (Upper Mandeville Tip and Lindsey Slough islands), low natural levees are apparent adjacent to the channel edge. Average marshplain elevation relative to MHHW for Lindsey Slough (Table 4) may be erroneously low. This value is an outlier (-0.24 m MHHW),

TABLE 4. Breached-levee site histories; SR Delta = Sacramento River Delta, SJR Delta = San Joaquin River Delta.

Site	Hydro-geomorphic region	Date(s) leveed	Date(s) breached	Number of years leveed	Active restoration actions	Previous study	Prevalent habitat	Comments
Donlan	West Delta	1910-1920 (possibly 1870-80)	1937	17 - 27 (possibly 57 - 67)	COE / FWS restoration site. Dredged material islands created in 1985.	USFWS and USACE (1990)	open water and vegetated dredged material islands	
Lower Mandeville	SJR Delta	1918	1933?	15?	none		tidal wetland	Briefly used as County park. Breached during construction of Stockton Ship Channel.
Mildred	SJR Delta	1921	1983	62	none		open water	
Old Prospect West	SR Delta	1914-1918	1963?	45-49	none		open water and fringe wetland	Breached during construction of Sacramento Ship Channel
Sherman Lake	West Delta	1869, 1894?	1925 ?	31?, 56?	State acquired in 1912 for dredged material disposal; No evidence of disposal observed during site reconnaissance.		open water and tidal wetland	
Venice Cut	SJR Delta	1906	1933?	27?	Corps/USFWS restoration site. Dredged material islands created in 1986.	USFWS and USACE (1990)	open water and tidal wetland	Breached during construction of Stockton Ship Channel

Note: Breached-levee sites are previously-leveed areas currently subject to tidal action. May or may not be the site of active restoration efforts. Date leveed reflects the most recent reclamation only (Thompson, 1958).
Sources: 1937 aerial photos, NWI habitat mapping, Delta Atlas (1995), Jones & Stokes (1993), Estuary (1996), Cosby (1941), CDWR (1982), USDA (1913), Van Royen and Siegel (1959), Matthew et al. (1931), Thompson (1957) COE reports, PWA analysis, and field verification.

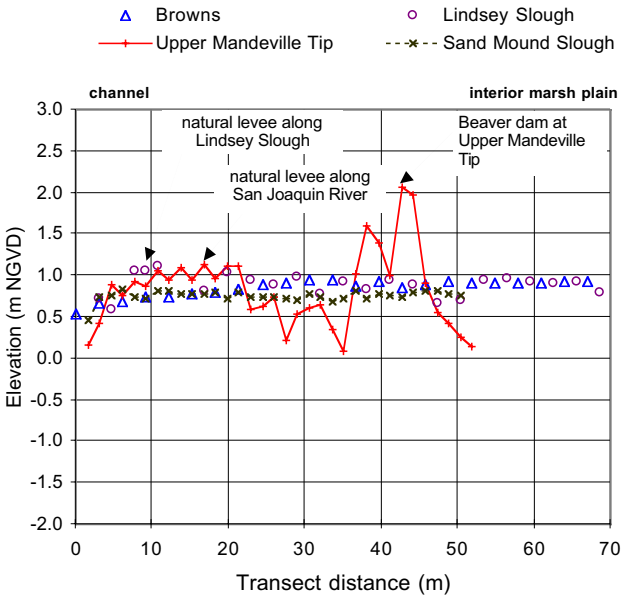

FIGURE 15. BREACH reference site elevation transects. Source: Field surveys, August 1998 (this study); abbreviations as in Table 3.

which we suspect may be a result of an inaccurate NGVD-to-MHHW conversion estimate (discussed previously). When expressed relative to NGVD, the Lindsey Slough average marshplain elevation is more consistent with those of other sites.

Natural levees occurred only at transects adjacent to fluvial distributary channels (i.e., Lindsey Slough and Upper Mandeville Tip transects). There were no levees on the tidal slough (non-distributary) channels of either Browns or Sand Mound Slough islands.

At Lindsey Slough, maximum levee height was 0.31 m above the average marshplain elevation. The natural levee at Lindsey Slough supported mature riparian vegetation, including large trees over ~0.2 m in diameter. At Upper Mandeville Tip, the maximum levee height above the marshplain is difficult to estimate because of inconsistencies in the marshplain surface. The natural levee at Upper Mandeville Tip was less distinctively vegetated, with tule and small diameter trees interspersed.

The data show slightly higher marshplains in areas near fluvial sediment sources (rivers or upland creeks). Marshplain elevations are higher at Browns (at the confluence of the Sacramento and San Joaquin rivers) and Lindsey Slough (in the Yolo Bypass) than at Sand Mound Slough (tidal flows only). The higher marsh elevation at Browns may also reflect higher flocculation and sedimentation rates for fines in the higher salinity west delta. No noticeable difference in marshplain elevation was evident between the Sacramento River and San Joaquin River deltas. A hypothesis that marsh elevations were higher in the Sacramento River delta because of the higher riverine water levels and riverine sedimentation is not supported by this data.

Breached-Levee Sites

Marshplain elevations for the breached-levee sites were consistently lower than for the corresponding natural reference sites. In the Sacramento River delta, average marshplain elevations at Old Prospect West were 0.22 m lower than at Lindsey (Table 4; Fig. 16). In the San Joaquin River delta, average marshplain elevations at Lower Mandeville Tip were 0.51 m below those of Sand Mound Slough (Table 5; Fig.17), the nearest reference site for which average marshplain data are available. In the west delta, average marshplain elevations at Sherman were 0.48 m lower than at Browns (Table 4; Fig. 18).

Once a breached site becomes vegetated, it appears that subsequent accumulation continues at a slow rate relative to sea level. Surprisingly, the average marshplain elevation at Lower Mandeville Tip (0.45 m MLLW) is only slightly higher than the minimum elevation for pioneer vegetation colonization (0.4 m MLLW). Since findings from the aerial photograph analysis indicate that the site was presumably at or above the pioneer elevation when it breached in 1933, the site gained little if any elevation relative to sea level in 65 years (~0.8 mm yr^{-1} assuming an initial elevation of 0.4 m MLLW). Rates of elevation change for the other vegetated breached sites (Sherman and Old Prospect West) are not known.

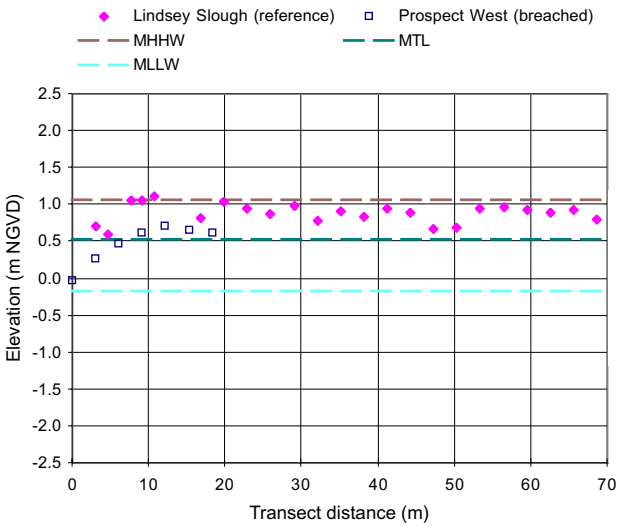

FIGURE 16. Elevation transects at BREACH study sites in the northern delta. Source as for Fig. 15; abbreviations as for Table 3.

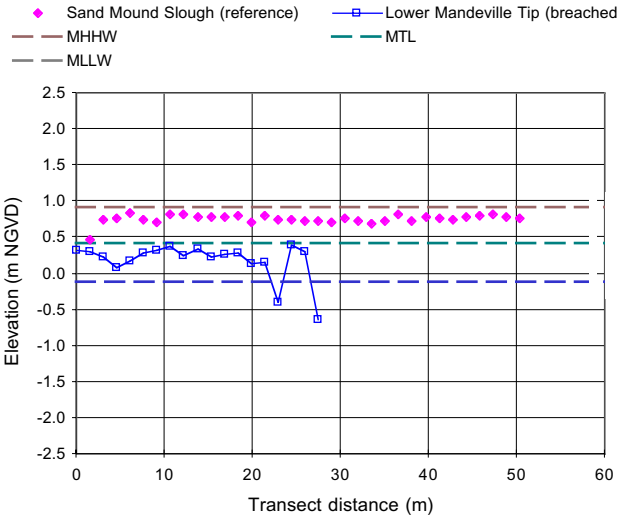

FIGURE 17. Elevation transects at BREACH study sites in the central delta. Source as for Fig. 16; abbreviations as for Table 3.

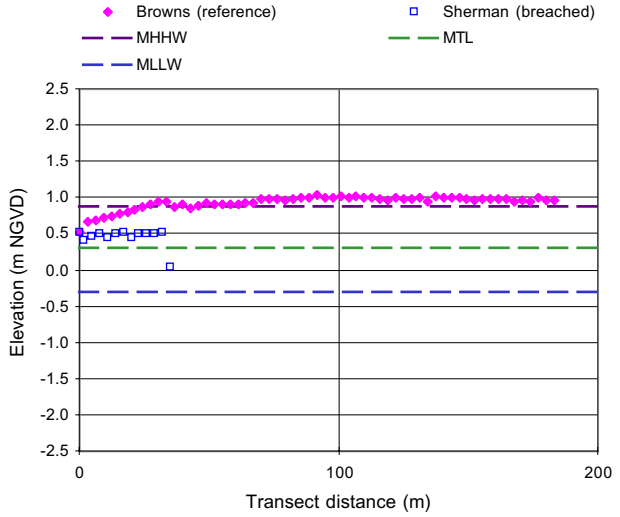

Figure 18. Elevation transects at BREACH study sites in the western delta. Source and abbreviations as for Fig. 16.

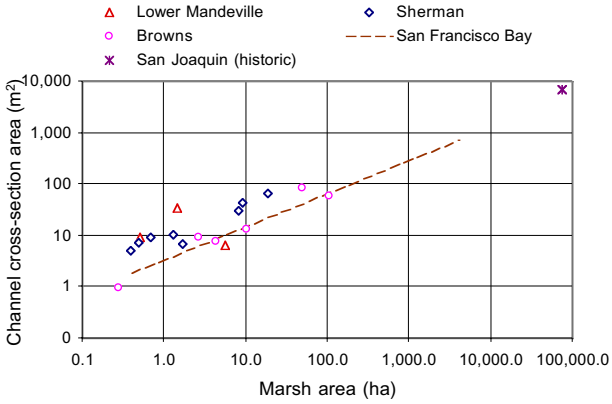

FIGURE 19. Tidal channel cross-sectional area as a function of marsh area. Sources: PWA field surveying (August 17, 1998) and USCGS (1867).

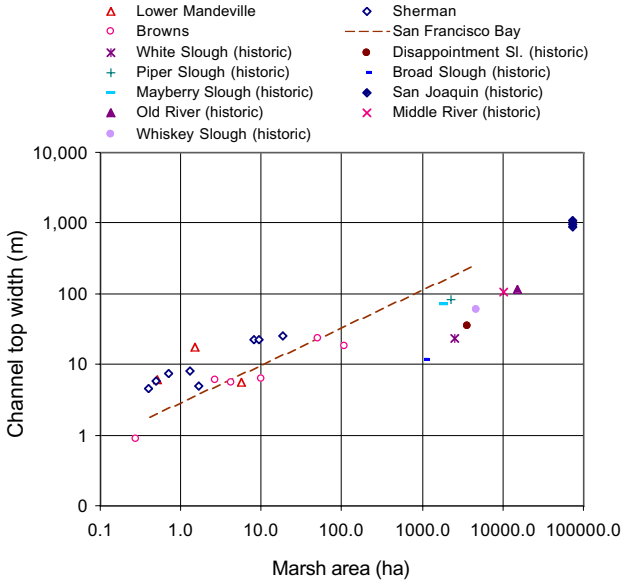

FIGURE 20. Tidal channel top width as a function of marsh area. Sources: PWA field surveying (August 1998), Atwater (1982), and U.S. Coast and Geodetic Survey (USCGS) (1867). Note: Data points for the historical San Joaquin represent three separate cross-sections near the Sacramento River confluence.

Tidal Channel Hydraulic Geometry

Natural tidal channels in the delta (as represented by Browns Island and the historical channels) appeared to be deeper than natural channels in San Francisco Bay but otherwise similar in width and cross-sectional area (Figs. 19–21). Top widths for Browns and the historical San Joaquin were similar to the bay, but other historical channels appeared to be narrower than the bay trend line (Fig. 20). This is likely a function of underestimating the historical channel widths.[4] The historical San Joaquin matches almost exactly the extrapolated bay trend line on all hydraulic geometry measures.

[4]These historical channel widths are based on Atwater (1982). Atwater's mapping was never intended as a precise representation of historical channel width, and it used methods that would have tended to underestimate channel width. Historical channel widths and locations were based on remnant channel traces visible in more recent aerial photographs. Because these traces are left by channel bottom deposits, they would correspond with bottom width, not top width.

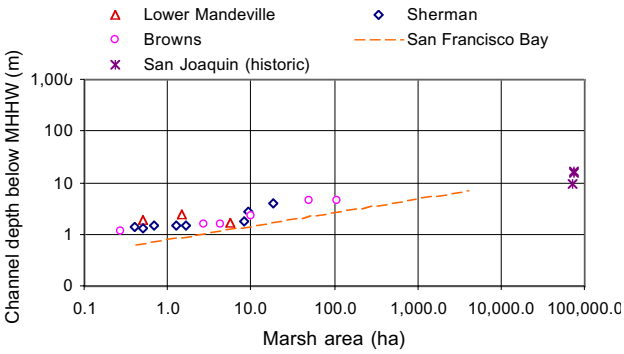

FIGURE 21. Tidal channel depth as a function of marsh area. Sources: PWA field surveying (August 1998) and USCGS (1867). See Fig. 20 for note.

Channels in the two breached sites (Lower Mandeville Tip and Sherman) tended to be larger in cross-section and wider than channels in the reference site (Browns) (Figs. 19–21). Larger cross-sections in breached-site channels would be predicted based on the larger tidal prism[5] carried by these channels. The lower marshplains in breached sites (see previous section) increases the tidal prism carried by the channel.

Refinements to Conceptual Model of Breached Site Evolution

Based on our preliminary results, the following refinements can be made to the conceptual model:

- Initial rates of subtidal accumulation in deep, open-water areas appear to be much greater than rates of sea level rise (47–51 mm yr^{-1} for Mildred Island, including the initial sediment pulse at breaching).
- Franks Tract appears to provide an example of a site that has reached equilibrium in the open-water condition. Other potential open-water equilibrium sites are Sherman Lake and Big Break.
- Pioneer marsh vegetation establishes rapidly (within ~4 years) at elevations around 1 m MLLW (median 1 m; range ~+0.4 to +1.5 m[7]). Once established, vegetation spreads to lower elevations (median -0.3 m; minimum -0.6 m MLLW[8]) by lateral expansion from the initial patches. Lateral expansion proceeds at a slow rate (maximum of 1.5–3 m yr^{-1}) and requires sheltered, low wave energy conditions.
- Although the presence of vegetation reduces the potential for scour and promotes additional accumulation, the rate of elevation change following vegetation establishment can be very slow (~0.8 mm yr^{-1} or less relative to sea level at Lower Mandeville Tip). Breached site marshplains that have been vegetated for decades remain well below natural marshplain elevations. For example, the marshplain at Sherman Island has been vegetated for over 60 years and remains 0.38 m below MHHW (0.48 m below nearby Browns Island).
- Where wave energy is sufficiently high (due to long fetch lengths, boat wakes, etc.), erosion and retreat of marsh edge occurs (e.g., Lower Mandeville Tip).

The above conclusions, based on preliminary results, should be confirmed through additional studies.

Implications of the Conceptual Model for Restoration in the Sacramento–San Joaquin Delta

The conceptual model has the following implications for future delta wetland restoration:

- Shallowly subsided sites. Restoring tidal action to shallowly subsided sites (ground elevation approximately ≥0.4 m MLLW) is expected to result in rapid reestablishment of a vegetated marshplain. Where the remnant channel system is intact, a natural network of drainage channels will also reestablish.
- Moderately subsided sites. Restoring tidal action to moderately subsided sites (ground elevation ≥ -0.6 to -0.8 m MLLW) may eventually result in reestablishment of a vegetated marshplain through lateral colonization, but at a slow rate.
- Deeply subsided sites and natural sedimentation. Natural sedimentation and organic accumulation appear to be limited by high rates of sediment transport for the type of deeply subsided, high wind-fetch conditions typically encountered in the delta. Natural accumulation, therefore, cannot necessarily be relied upon to build ground levels to intertidal elevations amenable to vegetation establishment. Limiting wave action and wind-driven currents may be an effective way of speeding the rate of natural sedimentation although this method is untested.
- Deeply subsided sites and placement of artificial fill. Placement of fill may be required for restoring vegetated marsh to deeply subsided sites. Creation of ecologically valuable tidal channel habitat will require special design consideration, such as grading during construction.

[5]Tidal prism is the volume of water exchanged through a channel cross-section over the course of one tide cycle.
[6]See earlier discussion of the uncertainty associated with this data set.
[7]Ignoring outliers.

SEDIMENTARY PROCESSES

Introduction

Drainage of tidal wetlands usually results in subsidence of the land surface through direct dewatering of the substrate and enhanced aerobic decomposition of organic material in marsh soils. Over time, the lower elevations caused by this subsidence are exacerbated by sea-level rise. In the Sacramento–San Joaquin Delta, the surface of many former tidal marsh areas is now more 5 m below the height of the mean tide level. Restoration of these drained areas to tidal marsh habitat requires surface elevations within the range of tidal water level fluctuations, and progressive increases in surface elevation to keep pace with regional sea-level rise. The purpose of this component of the BREACH study is to evaluate rates of marsh surface sedimentation/accretion and elevation change in breached levee marshes within the delta, and to compare these rates to those in 'natural', unleveed marshes. In addition, the study will evaluate longer-term rates of sedimentation and the relative roles of organic and inorganic components in vertical soil development. This interim report presents the preliminary results of the contemporary rate studies encompassing changes documented from March 1998 to June 1999.

Sampling Design

The BREACH study design encompasses three regions of the delta that we hypothesize are characterized by different regimes of sediment supply and tidal energy—potential controlling factors on vertical accumulation processes (Fig. 2; Table 1). The northern delta area has relatively low tidal energy and high freshwater/sediment supply from the Sacramento-Yolo Bypass discharges. The western delta region is characterized by greater tidal energy, and both tidal and fluvial processes modulate sediment supply. The central delta area has low tidal energy and low freshwater/sediment supply. At the study areas with extensive tracts of marsh (i.e., Browns, Sherman, Prospect and Sand Mound), sites were established both adjacent to channels (edge) and approximately 25 m into the marsh (interior). At Lower Mandeville Tip, sites were established on the marsh edge at two locations on the creek network—downstream and upstream.

Methods

Sedimentation on the marsh surface is measured as vertical accretion of material over an artificial marker horizon placed at the surface when the study was begun. White feldspar was laid on the marsh surface at each site in three 0.5- x 0.5-m plots. Approximately 0.5 cm of feldspar was applied in each case (Fig. 22). On subsequent sampling visits, cryogenic coring was used to extract a small frozen core from the marker plot, enabling direct measurements of the accretion above the white feldspar layer (Fig. 23).
Figure 22. Newly established 0.5-m x 0.5-m feldspar plot.
Figure 23. Frozen core shown feldspar marker.

Processes other than those operating directly at the surface can affect marsh surface elevation. Thus, a sediment-erosion table (SET) is used to integrate the effects of pro-

FIGURE 22. Newly established 0.5-m x 0.5-m feldspar plot.

FIGURE 23. Frozen core shown feldspar marker.

cesses over the upper 3–5 m of the substrate. The SET (Boumans and Day 1993) consists of an arm temporarily inserted into a deep basepipe. Pins are then inserted through a plate on the arm and successive measurements track changes in marsh surface elevation relative to the base of the pipe (Fig. 24). In this study, basepipes were inserted to refusal with a vibracore system (Fig. 25). Pipes were approximately 9 m in length and penetrated over 8.75 m at the interior site on Browns Island.

Shallow cores were taken at selected sites in November 1998 for radiometric dating to determine longer-term rates of sedimentation in marsh soils. Synthesis of these data with the accretion and SET data is ongoing. Rates for ^{210}Pb sedimentation are reported here for only some sites for which data are available. Sedimentation rates derived using ^{210}Pb incorporate the effects of compaction, decomposition, etc., over longer time frames and greater substrate depths than the accretion measures made using marker horizons, and we expect this technique will yield lower rates of sedimentation than are annually measured at the marsh surface.

At each site, temporary boardwalks are installed during each site visit to prevent disturbance of the surface where measurements are made. PVC markers are used to delineate the site and to aid relocation (Fig. 26). For both methods, baseline measurements were taken in March 1998 and data for seasonal intervals through June 1999 are reported here.

FIGURE 24. Sediment erosion table (SET).

FIGURE 25. Insertion of base pipe using a vibracore system.

Results

Northern Delta

Northern delta sites were not measured in June 1998 because of logistical difficulties. At all sites in the northern delta, accretion exceeds elevation change (Fig. 27). At the edge of the marsh in Old Prospect West, almost 40 mm of material accumulated over the marker horizon while elevation change was effectively zero. This means that while material was being deposited on the marsh surface, subsurface processes such as decomposition and compaction compensated for the new material and there was no net increase in marsh surface elevation. This phenomena has been termed shallow subsidence by Cahoon et al. (1995). In contrast, the interior site at Old Prospect West shows a similar amount of accretion and a net increase in marsh surface elevation of almost 30 mm. The reference site in the northern delta is Lindsey Slough on the marsh edge. The pattern here is similar to the Old Prospect West

FIGURE 26. Sand Mound Slough study site.

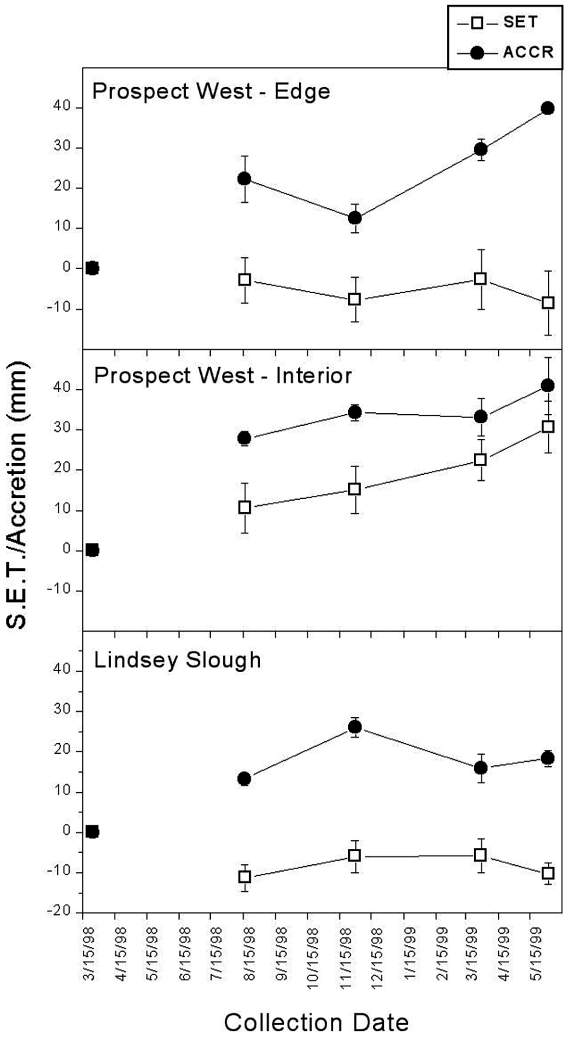

FIGURE 27. Results of marsh surface accretion (feldspar) and elevation change (SET) measurements at the northern delta study sites.

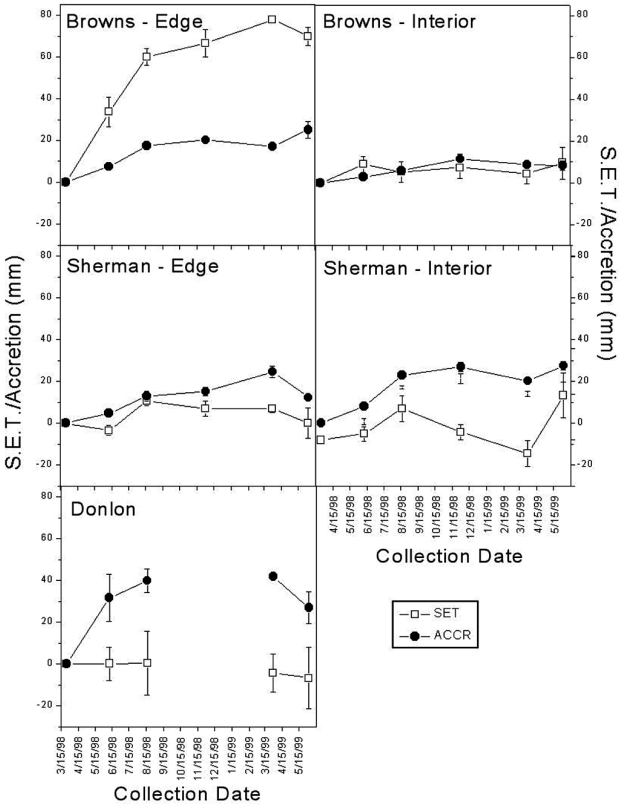

FIGURE 28. Results of marsh surface accretion (feldspar) and elevation change (SET) measurements at the western delta study sites.

edge site with accretion on the surface and no net increase in marsh surface elevation.

Western Delta

The natural site at Browns shows great differences between edge and interior sites (Fig. 28). The interior site shows low rates of accretion and elevation change with the two following the same pattern. In contrast, the edge site shows slightly higher accretion rates than the interior but a large increase in surface elevation. Over the period of sampling, the elevation of the marsh surface rose by approximately 70 mm at the Browns Edge site. Observation of this site between November 1997 and December 1998 suggests an increase in *Typha* spp. at the site relative to *Scirpus* spp. This may have caused an increase in belowground biomass, which could result in the elevation increase recorded by the SET.

At the breached levee site at Sherman Island, there is less difference between the edge and interior sites—for example, similar amounts of accretion over the year. Elevation change for the whole period is lower than accretion but not dramatically so. With the exception of the dramatic increase in elevation at the Browns Island Edge site, both Sherman and Browns islands show similar low rates of elevation change with accretion of approximately 10 mm at Browns at 20 mm at Sherman. Dating of the shallow cores from the edge sites using ^{210}Pb indicates rates of 0.8 cm yr^{-1} for Browns and 0.87 cm yr^{-1} for Sherman, clearly of similar magnitude to the accretion data.

The marsh site at Donlon Island, on dredged material introduced for marsh creation, shows essentially no elevation change over the period of record while there has been over 30 mm of accretion at the surface. This indicates that while material is accumulating, there are processes below the surface counterbalancing the accretion and maintaining a constant elevation.

Central Delta

Among the central delta sites, Lower Mandeville Tip data indicate a difference in pattern between upstream and downstream sites from August 1998 to March 1999 (data collection at Lower Mandeville Tip upstream sites did not commence until August 1998). Downstream elevation change and accretion track closely over time (Fig. 29). Both show rapid increases between March 1999 and August 1999 with little change thereafter. The upstream site shows almost 40 mm of accretion between August and March with no effective change in elevation—suggesting substantial influence of subsurface processes. Venice Cut, located on the opposite side of the Stockton Ship Channel in a marsh created with dredged material, shows a pattern of elevation change similar to that of the Lower Mandeville Tip sites. Elevation increases between March 1998 and August 1998 and there is little change through June 1999. This site, however, was subjected to substantial changes during this period as a large mat of wrack was deposited over much of the site between March and June 1998, and its subsequent removal has exposed a surface with only sparse vegetation in some areas.

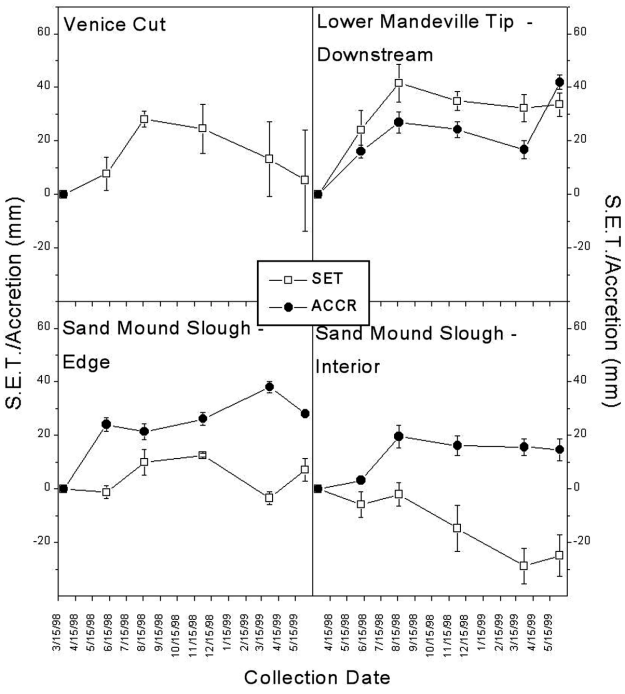

FIGURE 29. Results of marsh surface accretion (feldspar) and elevation change (SET) mesurements at the central delta study sites.

The reference site for the central delta is Sand Mound Slough. Both edge and interior sites here show shallow subsidence with elevation change lower than accretion. Indeed the interior site shows over 20 mm of elevation decrease over the first year of sampling. Accretion at the marsh edge over the entire period is approximately twice that of the interior site. Dating of shallow marsh cores using ^{210}Pb for the edge site at Sand Mound Slough shows a sedimentation rate of 1.13 cm yr^{-1} over the top 30 cm of marsh soil. These rates are of similar magnitude to the accretion rates measured on the marsh surface during the first year of this study and confirm the continued accumulation of material on the marsh surface at Sand Mound Slough.

Summary of Preliminary Results

The data presented here provide insight into the potential variation in marsh surface accretion and elevation change across the delta. Data synthesis is preliminary and additional data were collected in June 1999. However, some patterns are beginning to emerge from this assessment:

- All sites where feldspar marker horizons were recovered show at least 10 mm of accretion during the period of measurement.
- At most sites, more accretion occurs between March and August than between August and December.
- All sites in the central and western deltas show an increase in elevation between June and August (the slight apparent decrease at Browns Interior is not statistically significant), which may be attributed to seasonal accumulation of belowground plant biomass.
- Sites with high rates of accretion rarely show similarly high rates of elevation change.

Other components of the BREACH study have measured elevation, topography, and vegetation type at each of the sites. Incorporating these additional data sets will provide a more complete context for the consideration of these results. In addition, shallow cores taken in spring 1999 are being used to determine the relative contributions of organic and inorganic sediments to the accumulation of material on the marsh surface. These data will allow elucidation of the processes contributing to marsh accretion and elevation change across the study sites

BENTHIC INVERTEBRATES AND INSECTS

Introduction

Compared with the planktonic invertebrates prevalent in deep water channels of the delta, aquatic macroinvertebrates and insects associated with shallow-water habitats such as tule marshes contribute to more diverse food webs and presumably enhanced fish and wildlife production. Shallow habitats occupied by post-larval and juvenile fishes may be particularly important because of their role as nursery environments, providing refuge and food prior to the fishes' movements to deeper habitats. However, this benefit of shallow-water habitat to native fishes may be compromised under intense competition or predation by introduced fishes (see Fish, page 28).

Methods

We used benthic cores, fallout insect traps, and plankton nets to sample invertebrates and insects that would likely be available as food organisms to fish and wildlife in the shallow-water and SAV habitats. For that reason, we placed particular emphasis on the central delta sites where we were sampling fish, but benthic and pelagic macroinvertebrates and fallout insects were sampled routinely at all sites. Because of our objective of assessing the restoration goal of emergent tule marsh, emergent vegetation was the principal sampling strata at all sites. Riparian and SAV (water hyacinth, pennywort, parrots feather) habitats were also sampled if present; because they floated around the delta as a function of wind and currents, the SAV habitats were not consistently available for sampling at any one site. Our intended within-sampling strata replication was five samples, but this was reduced in cases where some samples were destroyed because of winds or other disturbances (e.g., insect fallout traps).

Results

Preliminary results are available for April–August 1998 sampling of benthic macroinvertebrates at the central delta, and for fallout insects from all central and some western delta sites.

Benthic Invertebrates

Preliminary comparison among different habitat strata across the four central delta sites indicates that the Upper Mandeville Tip reference site almost consistently has the highest total benthic invertebrate density (Fig. 30). However, variation (indicated by the 1 S.D. error bars) was so high that these differences are not likely significant. Mildred Island, the breached-levee site with the least developed tidal wetland, often has the lowest densities. There is no distinct trend in the distribution of macroinvertebrate density among the habitat strata.

Nematodes and oligochaetes typically dominate 20–90% of the numerical composition at all sites. While these benthic organisms play very important roles in delta ecosystems (e.g., as primary consumers), they typically do not appear in the diets of delta fishes (see Food Web Structure, page 31). The diets of delta fishes typically include crustaceans (copepods, isopods, amphipods) and insect larvae/pupae that showed differences among sampling sites and seasons.

Upper Mandeville Tip

At Upper Mandeville Tip, our central delta reference site, emergent marsh benthic invertebrate assemblages were dominated more by oligochaetes than any other habitat type (Fig. 31). Riparian habitats consistently had more crustaceans and insects (12–37%), and assemblages in the SAV habitats were most diverse. Compared with the emergent marsh benthos, benthic invertebrates in riparian and SAV habitats had greater proportions of amphipods; *Gammarus daiberi* characterized the riparian habitat, while *Crangonyx floridanus* was particularly prominent beneath water hyacinth and *Hyallela azteca* beneath pennywort. The isopod *Caecidotea racovitzae* was also found in greater prominence beneath water hyacinth and pennywort. Except for April, emergent insect (Chironomidae) larvae and pupae were not well represented in emergent marsh assemblages compared with SAV assemblages.

Lower Mandeville Tip

Lower Mandeville Tip demonstrated benthic macroinvertebrate assemblage structure similar to the reference site at Upper Mandeville Tip. The emergent marsh habitat was most dominated by nematodes and oligochaetes compared with the greater prominence of crustaceans in SAV habitat (Fig. 32). *Crangonyx floridanus* was more

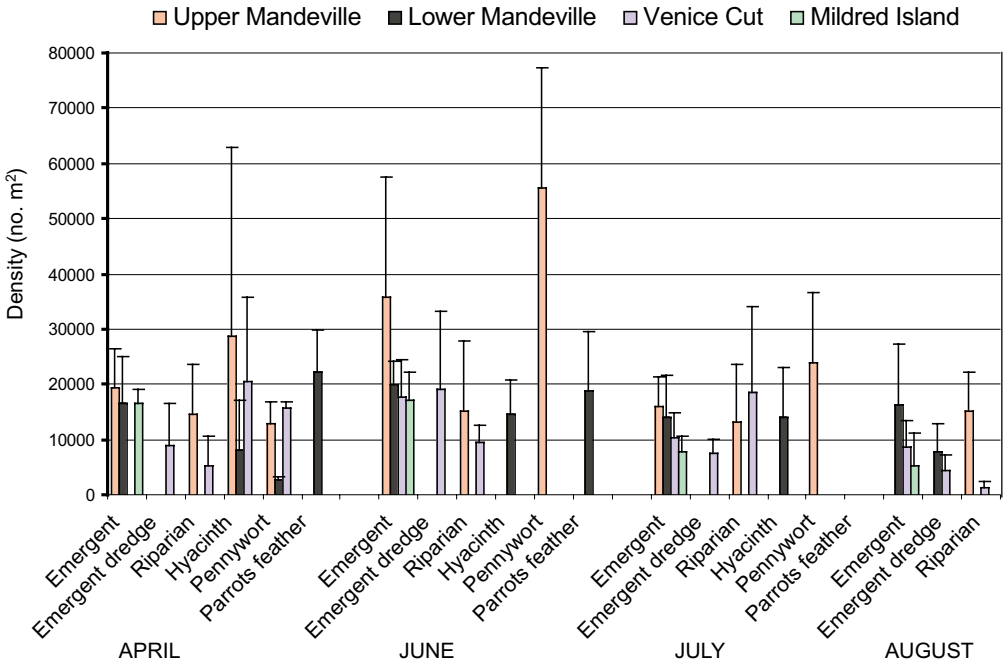

FIGURE 30. Densities of benthic macroinvertebrates in cores at four central delta sites, April-August 1998.

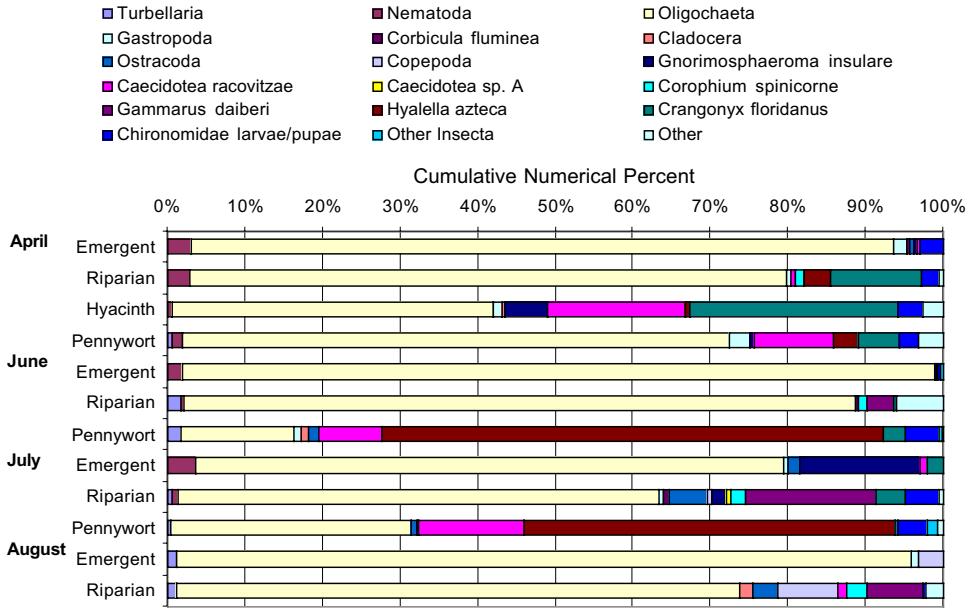

FIGURE 31. Numberical composition of invertebrates in benthic cores at Upper Mandeville Tip, April–August 1998.

prevalent in assemblages beneath SAV, particularly parrots feather in June (~25% of total organisms) and water hyacinth (~35%) in July.

Venice Cut

While nematodes and oligochaetes (also significant numbers of turbellarians in July) also dominated macroinvertebrate assemblages at Venice Cut Island, the assemblage differed from Upper Mandeville Tip and Lower Mandeville Tip with higher proportions of crustaceans in June and July and increased contributions of ostracods and chironomid larvae and pupae (Fig. 33). Correspondingly, both *Hyallela azteca* and *Crangonyx floridanus* did not represent as significant a portion of the benthos as they did at either Mandeville Tip site (especially Upper Mandeville Tip). An intrigu-

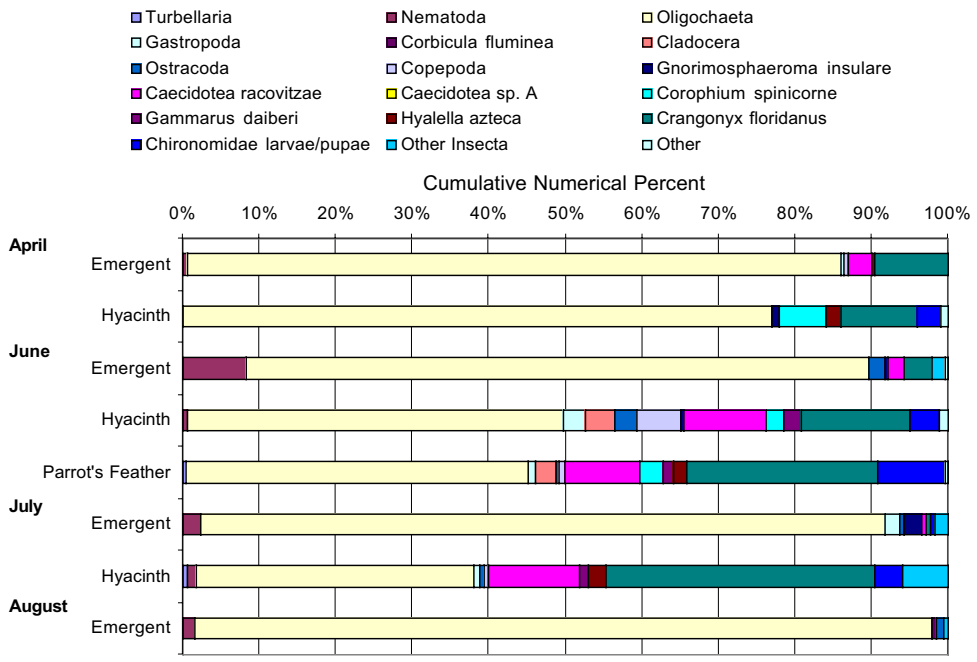

FIGURE 32. Numerical composition of invertebrates from benthic cores at Lower Mandeville Tip, April–August 1998.

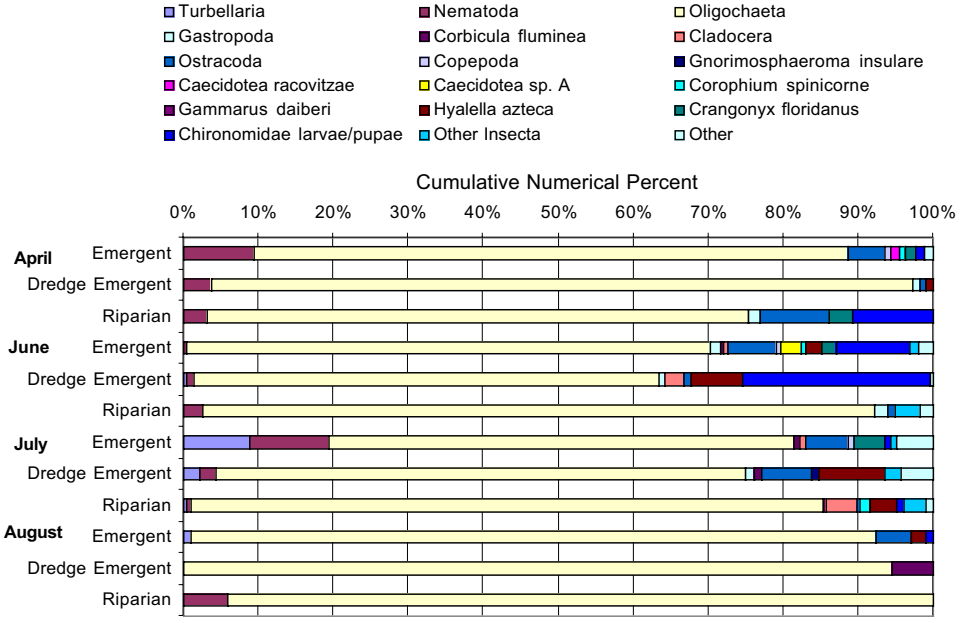

FIGURE 33. Numerical composition of invertebrates from benthic cores at Venice Cut, April–August 1998.

ing preliminary result was the greater contribution of crustaceans to the benthos of emergent marsh habitat that has developed on the dredge material at this site. Compared with the natural emergent marsh, these assemblages demonstrated higher proportions of chironomid larvae and pupae (June) and the greatest proportions of *Hyallela azteca* of any month. This may be associated with differences in sediment composition, which will be assessed after we have completed processing those samples.

Mildred Island

The limited shallow-water habitat available at Mildred Island precluded any comparisons other than seasonal com-

position of the emergent marsh macroinvertebrate assemblage (Fig. 34). As at the other sites, benthic macroinvertebrates were most diverse in June when the gammarid amphipods *Corophium spinicorne*, *Gammarus dailberi* and *Hyallela azteca* became abundant.

Insects

The density of fallout insects is relatively consistent among April–August sampling periods, with many samples averaging less than 2,000 individuals m^{-2}, but others exceeding 6,000–10,000 individuals m^{-2} (Fig. 35). In April, insects falling out in the emergent marsh are typically less dense than in SAV habitats, especially pennywort and hyacinth (particularly at Venice Cut). During the same month, however, fallout insects in emergent marsh at the western delta sites (Browns, Donlon and Sherman islands) are comparable and exceed densities at the central delta sites. In June, emergent marshes in both the central and western delta sites produce high densities of fallout insects, matched only by very high densities in the Venice Cut riparian habitat. Densities decline slightly in August although emergent marsh insects often approach or exceed 4,000 individuals m^{-2} (Upper Mandeville Tip, Venice Cut).

Collembolans and chironomids dominate the fallout insect numerical composition (Fig. 36).

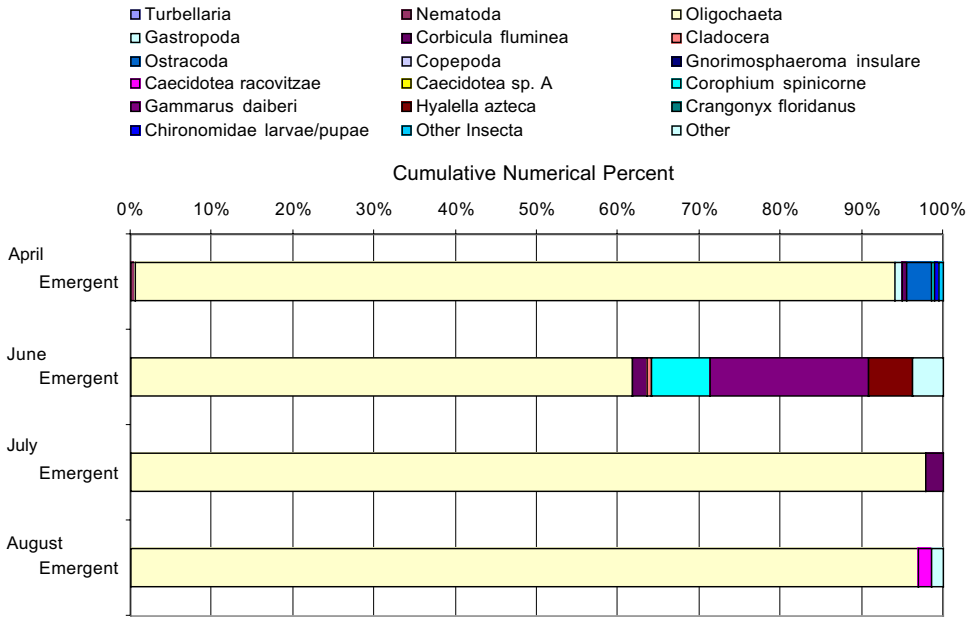

FIGURE 34. Numerical composition of invertebrates from benthic cores at Mildred Island, April–August 1998.

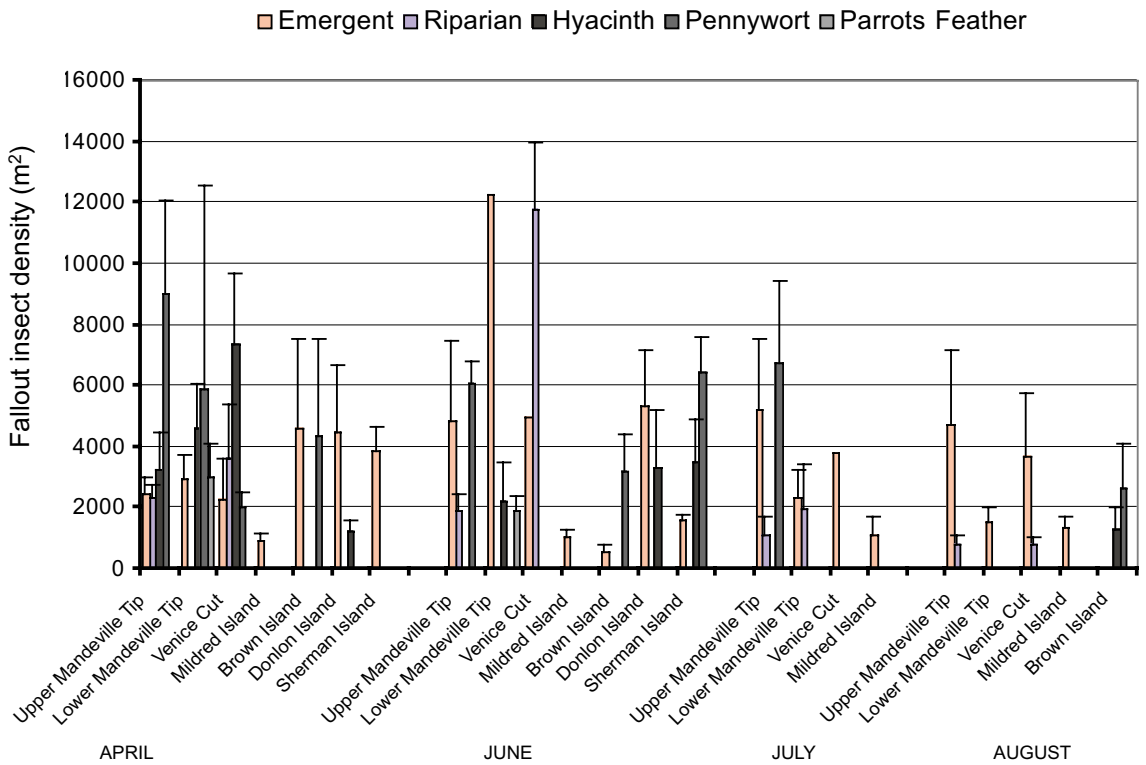

FIGURE 35. Density of fall-out insects at four central delta study sites, April–August 1998.

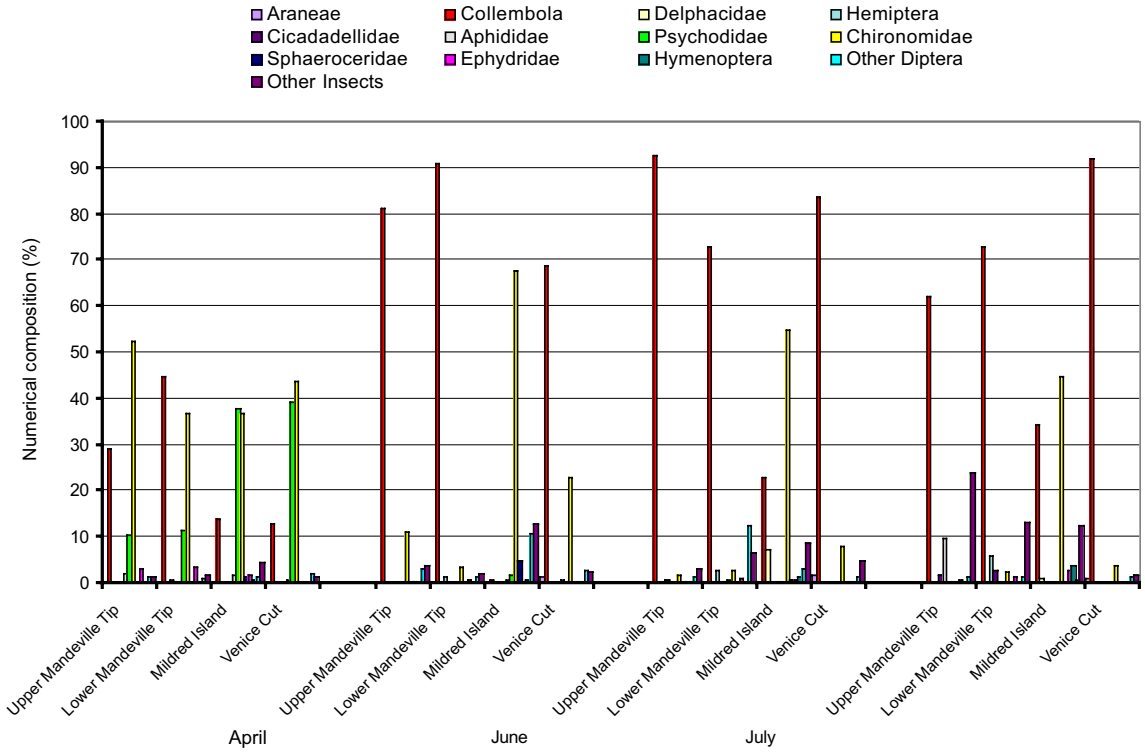

FIGURE 36. Numerical composition of fall-out insects at four central delta study sites, April–August 1998.

FISH

Introduction

The purpose of this section is to provide baseline information on fish assemblages and species use among habitat types at each study site. In conjunction with data from other BREACH study components, we will develop a conceptual model on the timing and composition of the fish community expected to use a flooded island given an array of physical (e.g. sedimentation rate) and biological (e.g. invertebrate assemblage) attributes. We anticipate the results from this component will provide critical information necessary to predict whether various breached levee restoration strategies currently contemplated in the CALFED planning process will provide the expected ecosystem benefits to resident and migrating native fishes in the delta. Through this study, we will attempt to answer the following questions:

- Does the fish assemblage vary between restored sites and the reference site?
- Does the fish assemblage (species type and abundance) vary with habitat type?
- What factors (e.g., time of day, habitat type, food availability, season) appear to be responsible for detected variations in the shallow-water fish community?

Study Area

The fish sampling element is only conducted in the central delta. The study sites include a reference site (Upper Mandeville Tip) and three breached-levee restoration sites (Lower Mandeville Tip, Venice Cut Island, Mildred Island).

Methods

We began sampling for larval and juvenile fish in April 1998 using five gear types: (1) modified plankton net, (2) larval light trap, (3) purse seine, (4) block net enclosure with depletion seining, and (5) beach seine. Sampling was conducted nearest to the two neap tides per month, April–September 1998. Sampling decreased to one neap tide per month for October–December 1998. In January 1999, we resumed sampling two neap tides per month and continued this effort through July 1999.

At each study site, larval fish were sampled by towing a plankton net along the edge of emergent vegetation and in unvegetated open water. Larval fish densities between emergent edge tows and open water tows were analyzed using a Wilcoxon matched pairs test. Juvenile fish were sampled in intertidal and subtidal zones with enclosure seines and purse seines. We stratified the study areas into emergent edge with and without submerged aquatic vegetation and open water (offshore). We randomly sampled for fish within these stratified habitat types. SAV type (e.g., *Egeria densa*) and density (classified as none, sparse, moderate or high) were recorded prior to sampling vegetated areas. A Kruskal-Wallis ANOVA was used to detect differences in fish density (catch per m^2) between habitat types at each study site.

Diet analyses from these fish collections are reported in Food Web Structure (pg. 31). On occasion, we also did on-site diet analysis on large piscivores (> 200 mm FL). The stomach contents from these fish were identified, counted and recorded on data sheets.

Preliminary Results and Discussion

To date, 35 fish species (8 native and 27 introduced) have been collected at all study sites. Over 98% of the total fish collected are non-migratory residents. Migratory species collected include chinook salmon (native), striped bass (*Morone saxatilis*, introduced) and American shad (*Alosa sapidissima*, introduced). Approximately 99% of the catch (larval and juvenile fish) was introduced species (Figs. 37 and 38).

The density of all native fish species combined is significantly higher (Kruskal-Wallis with ranked Tukey, $P < .05$) at Upper Mandeville Tip (reference site) compared with other breached levee study sites (Fig. 39). The density of all introduced fish species combined is significantly different (Kruskal-Wallis with ranked Tukey, $P < .05$) between study sites (Fig. 3). These preliminary results suggest that historical ecological functions of the reference site provide essential habitat features for native fish. We are continuing to examine this issue through further synthesis of data collected through 1999.

Our preliminary results also show that fish distribution and occurrence is influenced by physical habitat attributes—specifically, water temperature and SAV. Native fish spawn (Fig. 40) and reared (Fig. 41) during a constricted temporal window in the early spring months under a cool temperature regime (10–18°C). In contrast, introduced fish spawn (Fig. 40) and reared (Fig. 41) from

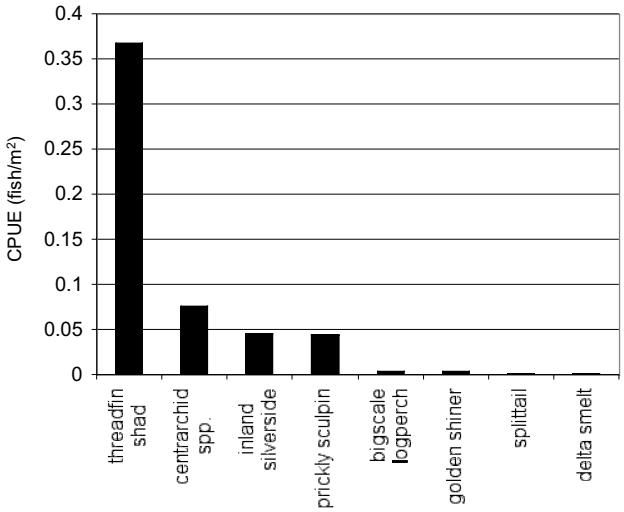

FIGURE 37. Relative catches (catch per unit effort [CPUE]; fish m^{-3}) of introduced and native fish larvae during BREACH sampling, April–December 1998.

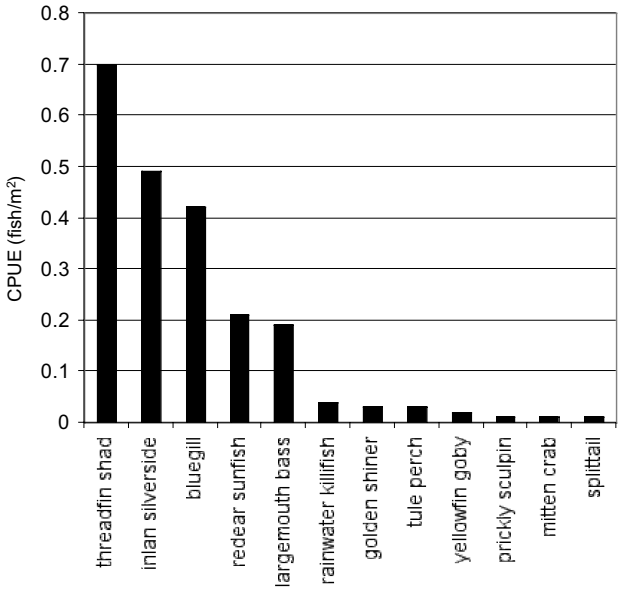

FIGURE 38. Relative catches (CPUE; fish m^{-2}) of introduced and native juvenile fishes during BREACH sampling, April–August 1998.

late spring into the early fall when temperatures were warmer (15–25˚C). Regarding SAV, densities of various fish larvae are significantly different (Wilcoxon, $P < .05$) between inshore-vegetated habitats and offshore-open water habitats (Fig. 42). Juvenile fish densities also are significantly different (ANOVA, $P < .05$) between SAV and open-water habitats (Fig. 43).

Stomach analyses were completed for largemouth bass

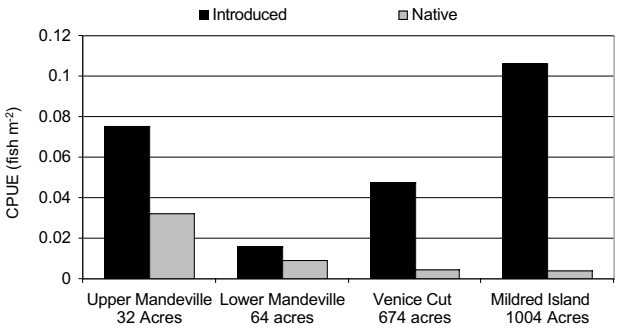

FIGURE 39. Relative density (CPUE, fish m^{-2}) of all introduced and native fishes during BREACH sampling at natural (Upper Mandeville) and three breached-levee (Lower Mandeville, Venice Cut, Mildred Island) study sites.

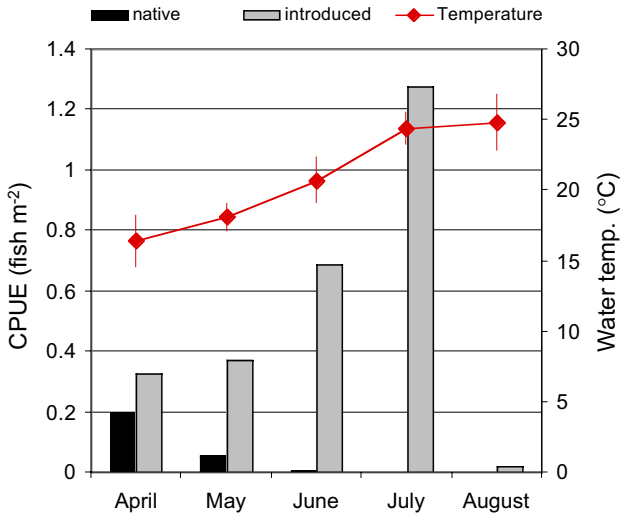

FIGURE 40. Relative density (CPUE; fish m^{-3}) of larval introduced and native fishes and temperatures during BREACH sampling during April–August 1998.

(*Micropterus salmoides*), white catfish (*Ameiurus catus*) and striped bass in 1998. We documented the presence of several juvenile fish in the gut contents of these species, including, splittail (*Pogonichthys macrolepidotus*, native), threadfin shad (*Dorosoma petenense*, introduced) and inland silverside (*Menidia beryllina*, introduced). The predatory impacts of introduced fish on native fish have yet to be determined. We will continue to examine this issue in 1999.

Working Hypotheses on the Role of Shallow-Water Habitat Supporting Native Fish in the Delta

We have developed the following hypotheses based on 1998 results:

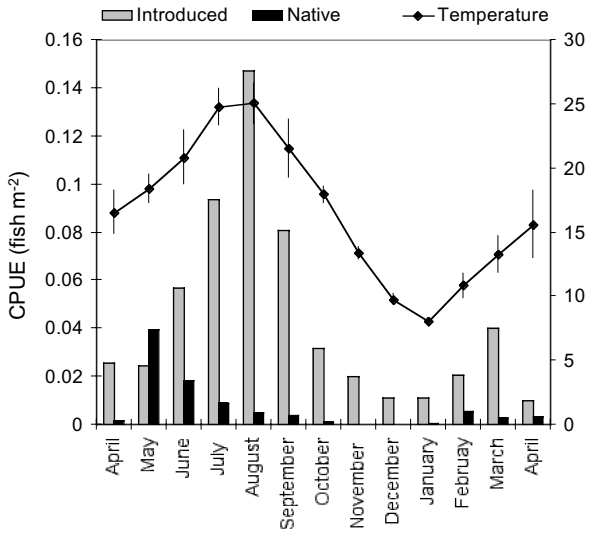

FIGURE 41. Relative density (CPUE; fish m^{-2}) of juvenile introduced and native fishes and temperatures during BREACH sampling during April 1998–April 1999.

- Restoring natural processes that promote habitat variability is important for recovery of native fish in the delta.
- Timing of spawning and length of rearing by various fishes is largely determined by water temperature.
- Abundance and distribution of fish occupying shallow-water habitat is strongly correlated with vegetation type and density.
- Predation may substantially limit native fish abundance in shallow-water habitats.

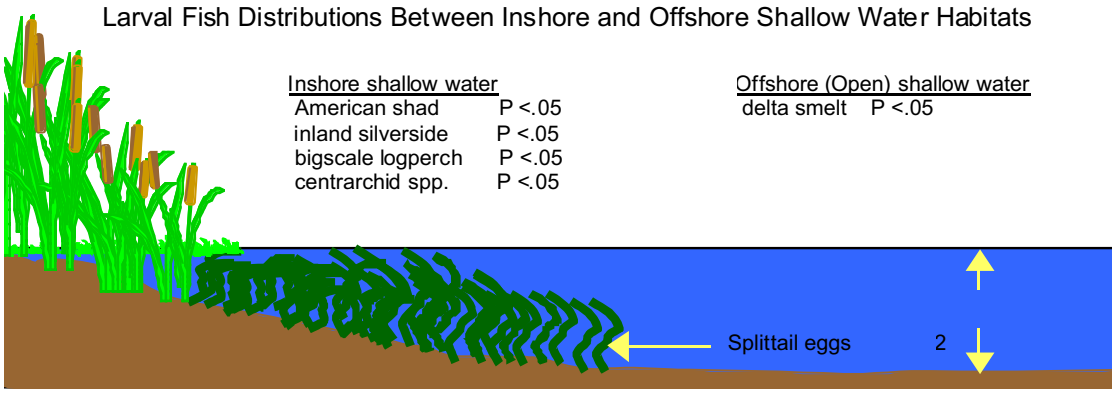

FIGURE 42. Differences in larval fish density between nearshore, vegetated and offshore, non-vegetated habitats during BREACH sampling. The species listed in this figure have a strong association with that habitat type. In April 1998, we collected splittail eggs attached to submerged vegetation in Venice Cut Island. This is the first documented catch of splittail eggs in the San Francisco Estuary.

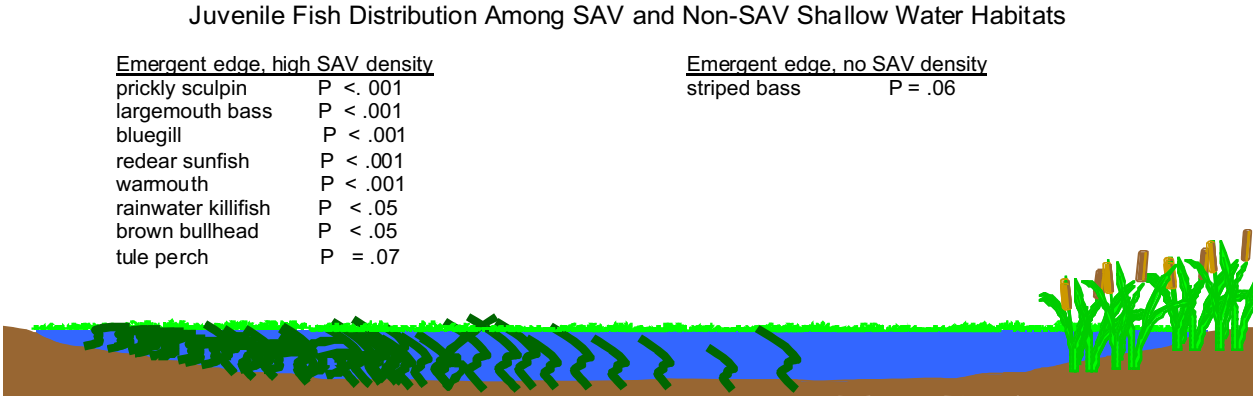

FIGURE 43. Differences in juvenile fish density between nearshore, vegetated and offshore, non-vegetated habitats during BREACH sampling. The species listed in the figure above have a strong association with that particular habitat type.

FOOD WEB STRUCTURE

Introduction

Increased habitat and trophic support of commercially and recreationally important fisheries resources is a prominent goal of estuarine and coastal wetland restoration. This is particularly the case for wetland restoration in the Sacramento/San Joaquin Delta, where populations of several fishes that are either listed or being considered as threatened or endangered may benefit directly or indirectly from restoration of tidal marshes and floodplains. However, we lack sufficient information to evaluate whether restoring wetlands contribute to enhanced fish production. Our BREACH comparison of natural and breached-dike wetlands in the delta provided us with the opportunity to evaluate one mechanism—food web linkages—to assess whether and how wetland restoration could contribute to recovery and sustainability of important fishes.

In our CALFED studies of the patterns and rates of breached-dike wetland development in the Sacramento-San Joaquin Delta, we compared diet compositions of fishes utilizing reference and breached dike sites to elucidate potential ecological relationships that link the development of breached-dike wetlands to the support of shallow-water fishes. We selected representative subsamples from the 1998–99 BREACH sampling of fishes in different habitat strata at four of our five central delta sites (Upper Mandeville Tip [reference]; Lower Mandeville Tip, Venice Cut, Mildred Island [breached]; see previous Fish section) for diet analyses that could be related to our corresponding sampling of potential benthic and epibenthic invertebrates, insects and zooplankton as potential prey resources at the same sites (see next section; Toft 2000).

Methods

Fish were retained from block net-depletion, purse, and beach seine samples and immediately preserved in 10% buffered formalin. We quantitatively analyzed individual stomach contents of up to five replicate fish from each habitat strata (emergent edge with and without submerged aquatic vegetation, and open water offshore), site, and month. Prey organisms were identified under light microscopy to the lowest possible taxonomic level, enumerated, and weighed; in addition, stomach fullness and the state of contents digestion were ranked using a standardized system (Terry 1977). Results are presented as percent of total Index of Relative Importance (IRI) values. The IRI is a composite, dimensionless indicator that equally weighs numerical and gravimetric composition and frequency of occurrence for each prey category (Pinkas et al. 1971). Based on our invertebrate sampling and literature information, we categorized prey taxa into five "habitat groups": benthic, epibenthic, phytal, planktonic, and neustonic/surface drift (Table **5**).

Results

We have diet composition data for seven common fish species captured during our sampling in the delta (see previous Fish section for more detail on fish assemblages and habitat associations), including four native (N) and three introduced (I) species:

- chinook salmon, *Oncorhynchus tshawytscha* (Walbaum) [N]
- splittail, *Pogonichthys macrolepidotus* (Ayres) [N]
- inland silverside, *Menidia beryllina* (Cope) [I]
- bluegill, *Lepomis macrochirus* Rafinesque [I]
- largemouth bass, *Micropterus salmoides* (Lacepède) [I]
- tule perch, *Hysterocarpus traski* Gibbons [N]
- prickly sculpin, *Cottus asper* Richardson [N]

Sample sizes of delta smelt (*Hypomesus transpacificus* McAllister), striped bass (*Morone saxatilis* [Walbaum]), and Sacramento pikeminnow (squawfish, *Ptychocheilus grandis* [Ayres]) were insufficient to provide comparisons. Thirty-eight prey categories originated from all five habitats, although phytal organisms were not well represented.

Prey spectra of these fish (Fig. 44) indicate considerable support by emergent insects, primarily chironomids occurring either as benthic larvae, epibenthic pupae, or drift emergents and adults. In shallow-water, emergent-edge habitats, amphipods such as *Gammarus daiberi* and *Hyalella azteca* were prominent epibenthic prey. The most common benthic prey were chironomid larvae while fish larvae and *Pseudodiaptomus forbesi* constituted the most common planktonic prey. Sources of the composite prey spectra (Fig. 45) indicate that epibenthic invertebrates tend to be the most important contributors to their diets except in the case of chinook salmon, which had a larger contribution from zooplankton, and splittail and inland silverside, which had consumed more benthic and neustonic/

TABLE 5. Prey taxa categories from seven species of common fishes in reference and breached-dike sites in the central Sacramento–San Joaquin River delta, 1998-1999 BREACH studies. Known exotic species are in bold.

Prey Taxa	Benthic	Epibenthic	Phytal	Planktonic	Nuestonic/ Surface drift
Algae	✓				
Oligochaetes	✓				
Stylaria lacustris		✓			
Hirudinea (leaches)	✓				
Gastropods (two spp.)	✓				
Bivalves	✓				
Araneae					✓
Acarina			✓		
Cladocerans				✓	
Ceriodaphnia sp.				✓	
Daphnia sp.				✓	
Eurycercus lamellatus		✓			
Simocephalus expinosus				✓	
Ostracods		✓			
Copepoda				✓	
Calanoid copepods				✓	
Pseudodiaptomus forbesi				✓	
Eurytemora sp.				✓	
Cyclopoid copepods				✓	
Isopods					
Gnorimosphaeroma insulare		✓			
Asellus hilgendorfii		✓			
Caecidotea racovitzae		✓			
Gammarid amphipods					
Gammarus daiberi		✓			
Hyalella azteca		✓			
Corophium spinicorne	✓				
Corophium stimpsoni	✓				
Crangonyx floridanus		✓			
Insects					✓
Zygoptera sp. nymph			✓		
Psocoptera					✓
Homoptera					✓
Aphididae					✓
Psychodidae					✓
Chironomidae-larvae	✓				
Chironomidae-pupae		✓			
Chironomidae-adults					✓
Sphaeroceridae					✓
Fish (*Cottus asper*) larvae				✓	

surface drift organisms. Prey specifically associated with emergent or submergent/floating plants were notable only in the case of largemouth bass.

Differences in prey sources among sites (Fig. 46) suggest that benthic and epibenthic prey contribute more in reference (Upper Mandeville Tip) and more mature sites (Lower Mandeville Tip, Venice Cut) than the more open-water sites (Mildred Island). However, seasonal differences may compound this interpretation, with a tendency in some species to feed less on epibenthic prey and more on neustonic/surface drift prey between winter–spring and summer.

Food web linkages between shallow-water habitat invertebrates and fish indicate that both emergent and aquatic vegetation habitats potentially contribute to prey resources of important fishes, with open-water prey entering into the diets of more planktivorous fishes at some sites during the spring.

Field examinations of piscivorous largemouth bass, white catfish, and striped bass found their gut contents to include several juvenile fish, including splittail (native), threadfin shad (introduced), and inland silverside (introduced).

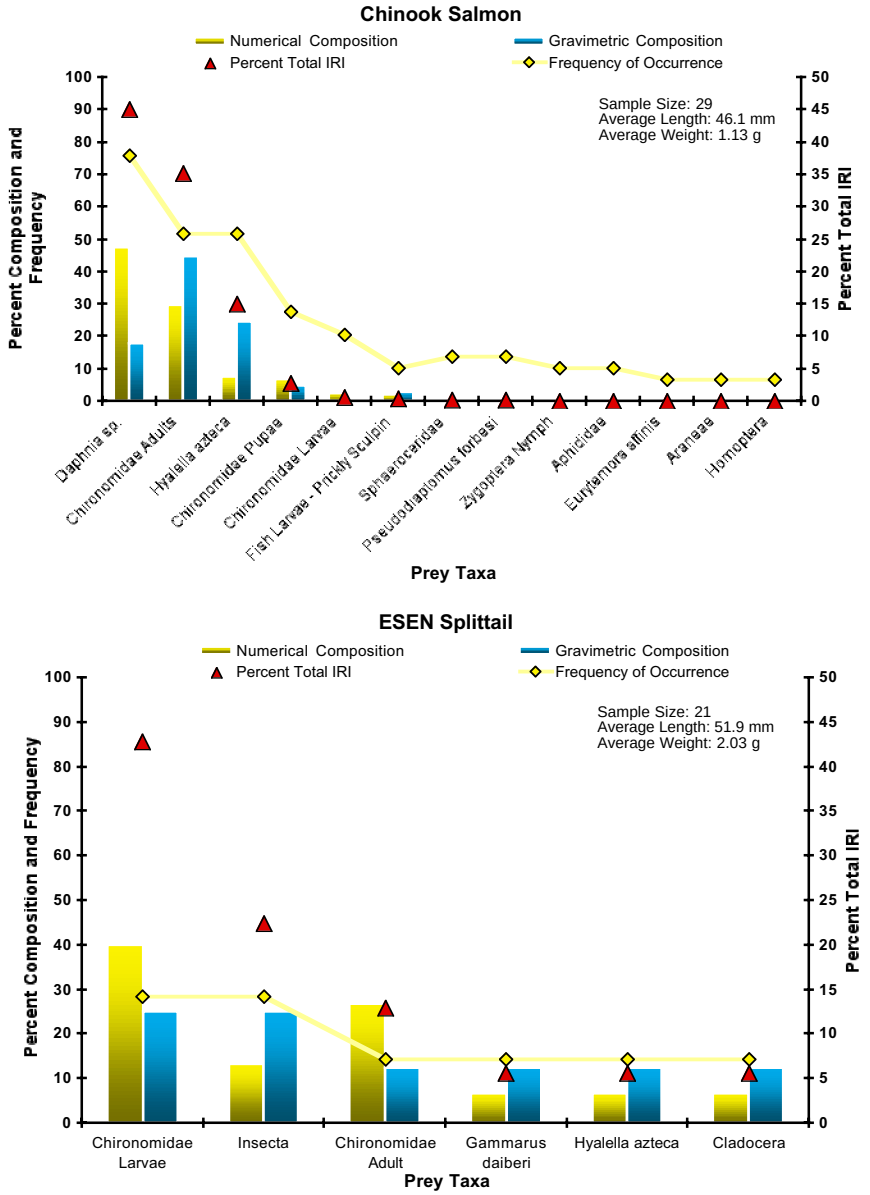

FIGURE 44. Prey spectra of seven common fishes in the central Sacramento–San Joaquin River Delta, 1998–99 BREACH studies; fish from emergent habitats are from block-depletion seine sampling and those from open-water habitats are from purse seine sampling.

Discussion and Conclusions

Food web linkages between shallow-water habitat invertebrates and fish indicate that both emergent and aquatic vegetation habitats potentially contribute to prey resources of important fishes, with open-water prey entering into the diets of more planktivorous fishes at some sites during the spring. For example, juvenile chinook salmon fed predominantly on chironomid larvae and pupae (more typical of emergent marsh) as well as the amphipod *Hyallela azteca*. Largemouth bass are principally piscivorous, but also prey on a wide variety of crustaceans and chironomid larvae/pupae. California silverside appear to reflect the predominant shallow-water habitat, preying upon planktonic cladocerans (*Daphnia* sp., *Simocephalus expinosus*, *Ceriodaphnia* sp.) associated with FAV in extensively flooded islands like Mildred Island (in April) but incorporating more emergent marsh macroinvertebrates (chironomid larvae/pupae, ostracods) at the Upper and Lower

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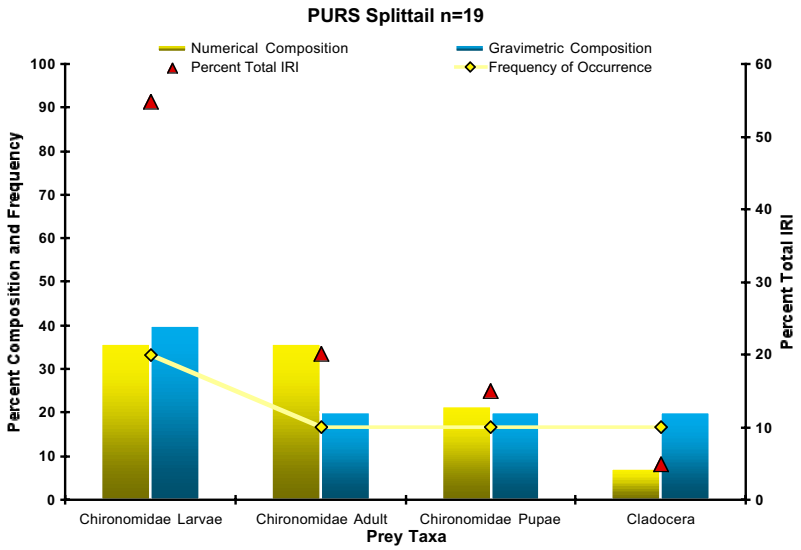

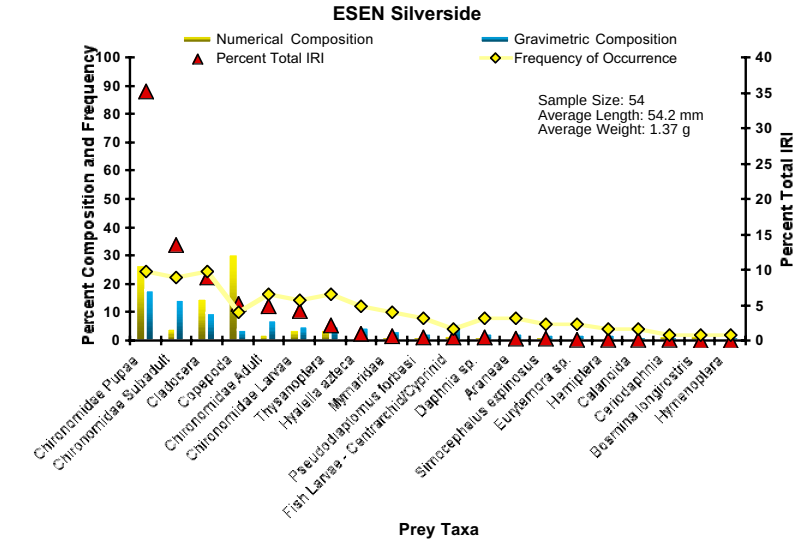

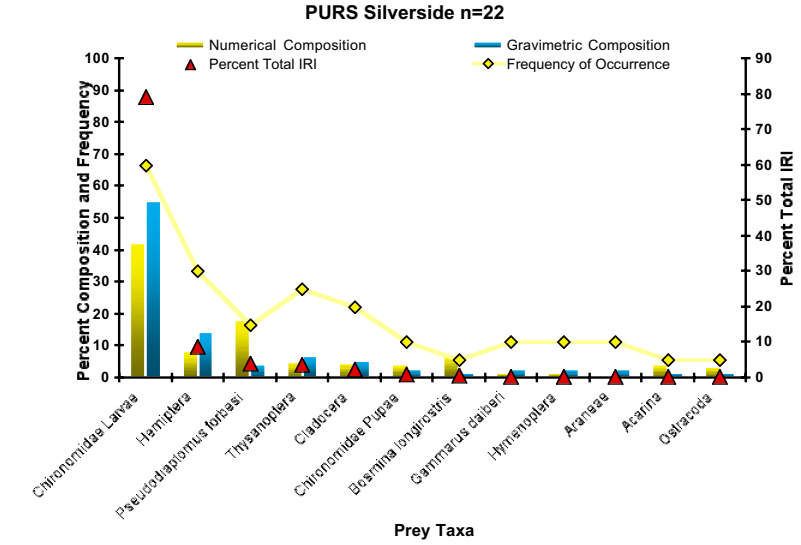

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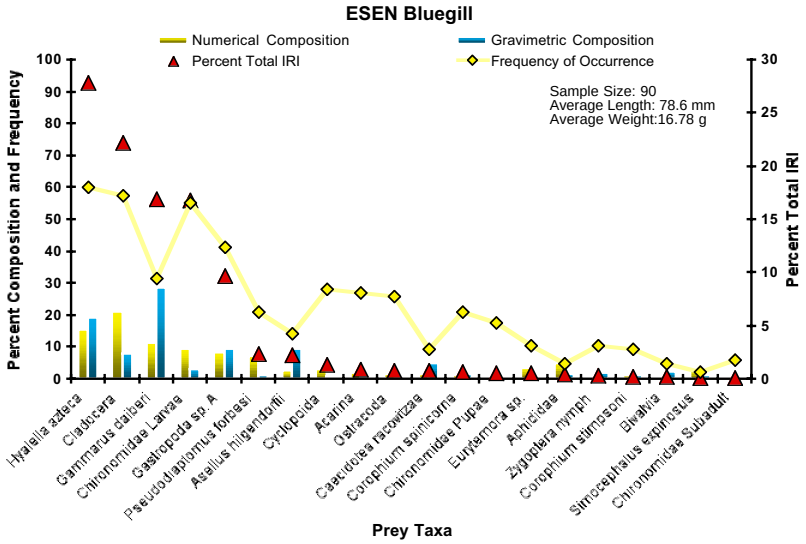

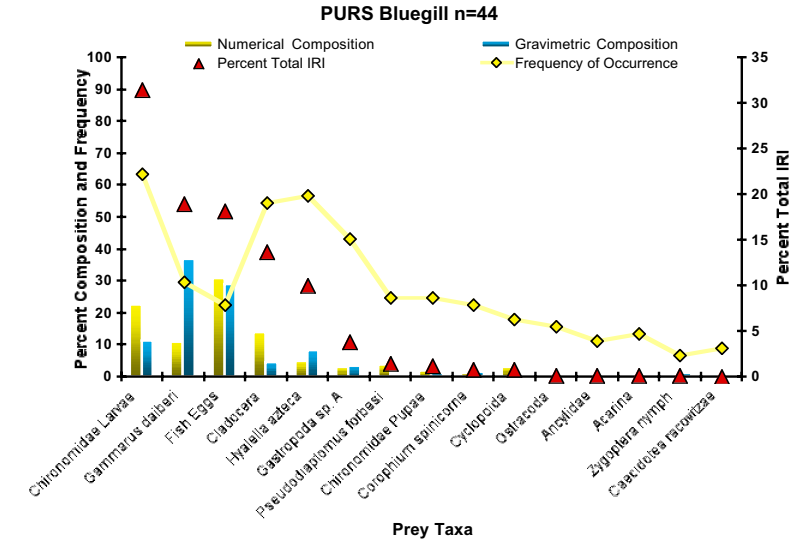

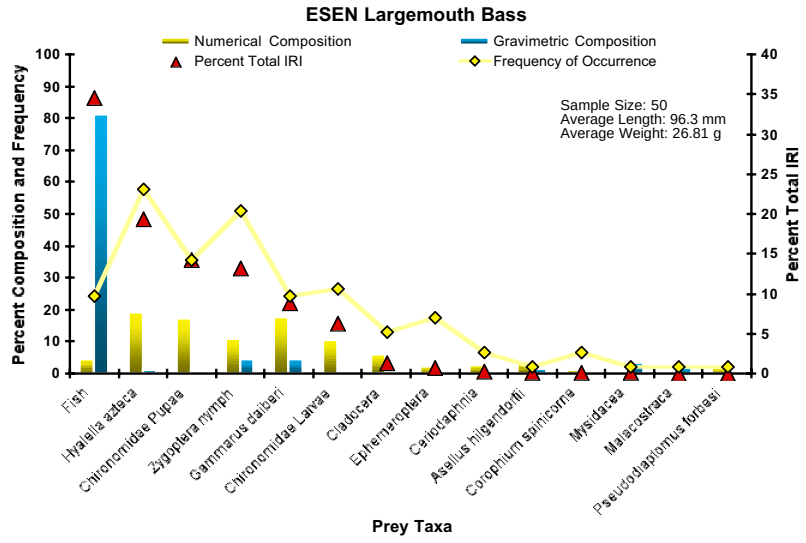

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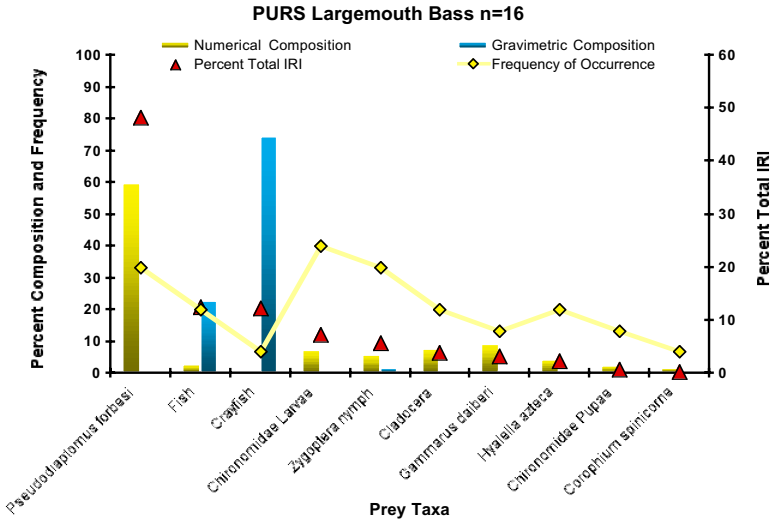

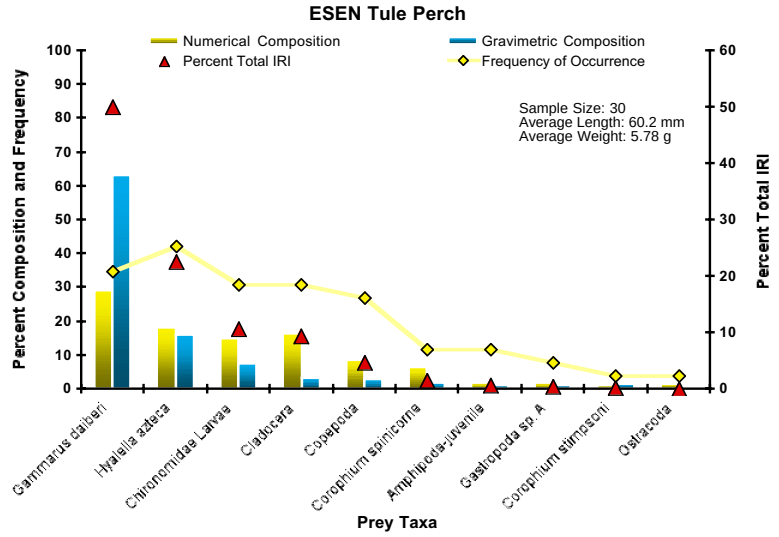

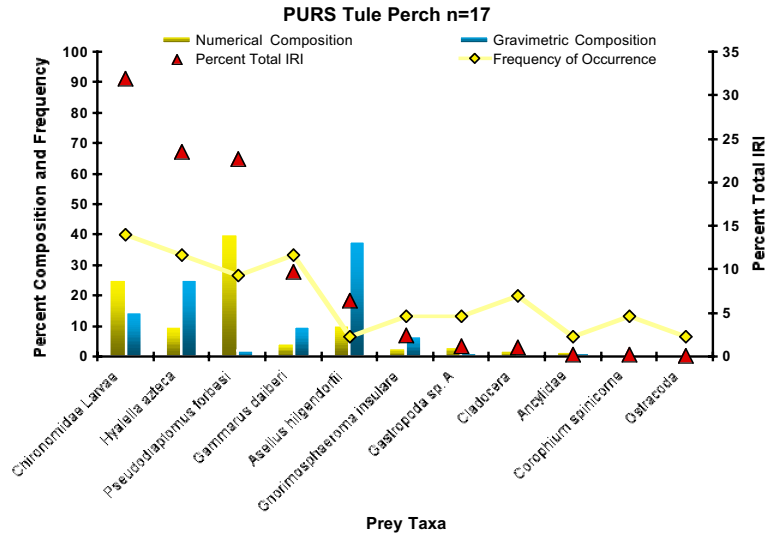

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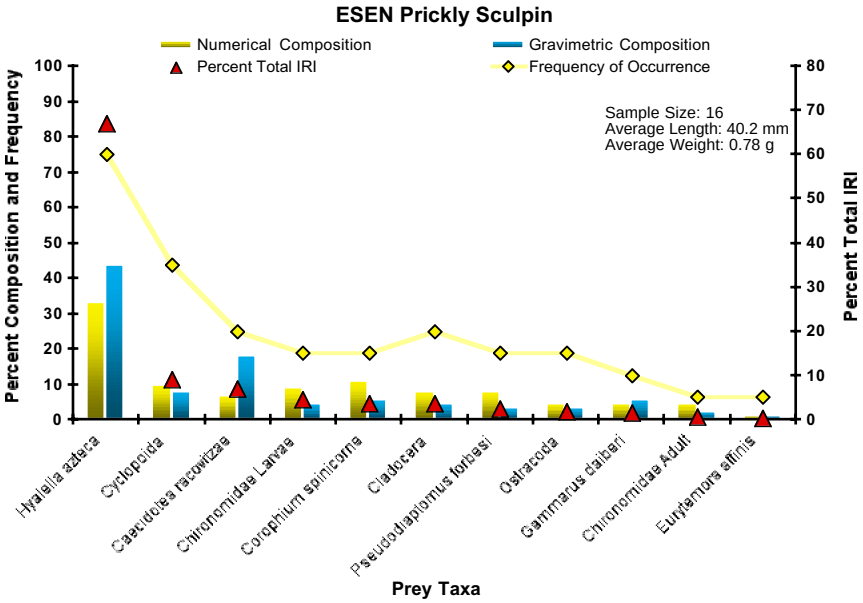

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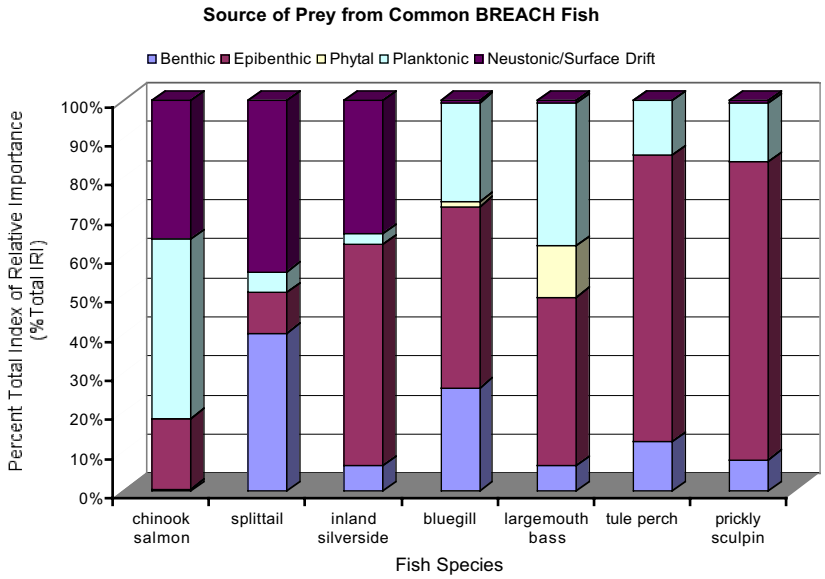


FIGURE 45. Proportional prey source contributions (% total Index of Relative Importance [IRI]) of common fishes in the central Sacramento-San Joaquin River Delta, 1998–99 BREACH studies.

Mandeville Tip sites. Seasonal differences are apparent, as silverside at Mildred Island had switched to emergent marsh chironomid larvae/pupae and fall-out insects (collembolans, homopterans, Araneae) in July. Both splittail and tule perch displayed diet spectra of open-water, FAV, and emergent marsh prey, including cladocerans, amphipods (*Hyalella azteca*), and chironomid larvae and pupae. Bluegill illustrated incredible diet diversity from all habitats, regardless of the site, indicative of a completely opportunistic feeder.

Our preliminary conclusions suggest that:

- With few exceptions, food web linkages to prominent fishes at our BREACH sampling sites originated predominantly from benthic and epibenthic production, or adjacent emergent or riparian wetland habitats in the case of some of the drift insect prey.
- Distinct trends in sources of prey among reference or breached-dike sites of different ages do not exist, although benthic and epibenthic prey tend to be more consistently present in the diets of fish at reference or

more mature breach-dike sites, while zooplankton and neuston/surface drift prey often dominate at the more open-water sites.

- Introduced prey species are common elements of prey spectra, especially the epibenthic gammarid amphipod *Gammarus daiberi* and the calanoid copepod *Pseudodiaptomus forbesi*. Three new exotic species that occurred in low abundances were also discovered: the amphipod *Crangonyx floridanus*, and the isopods *Caecidotea racovitzai* and *Asellus hilgendorfii*.

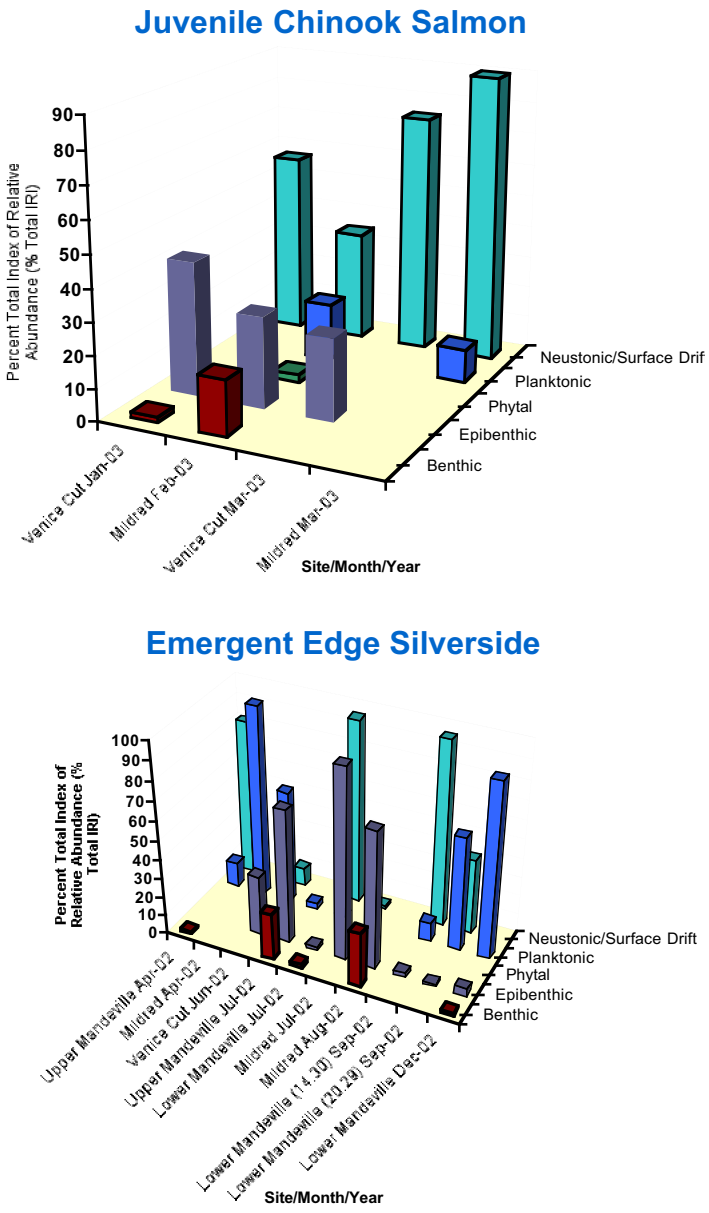
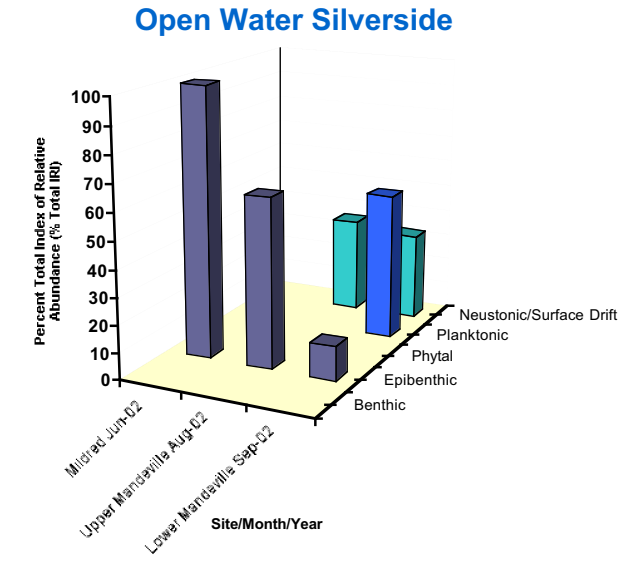
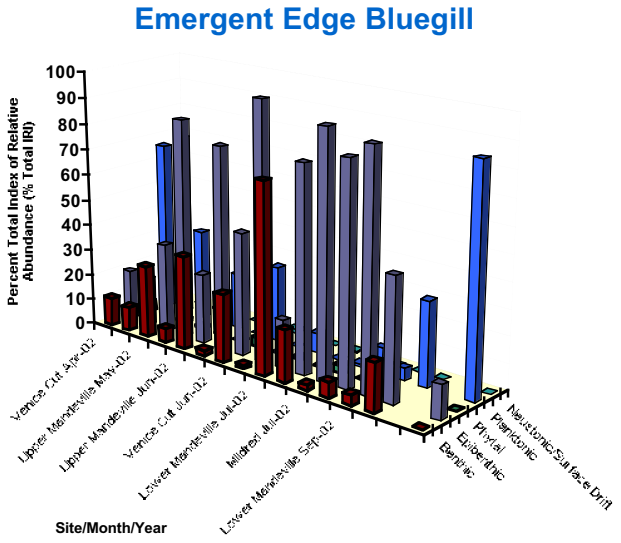
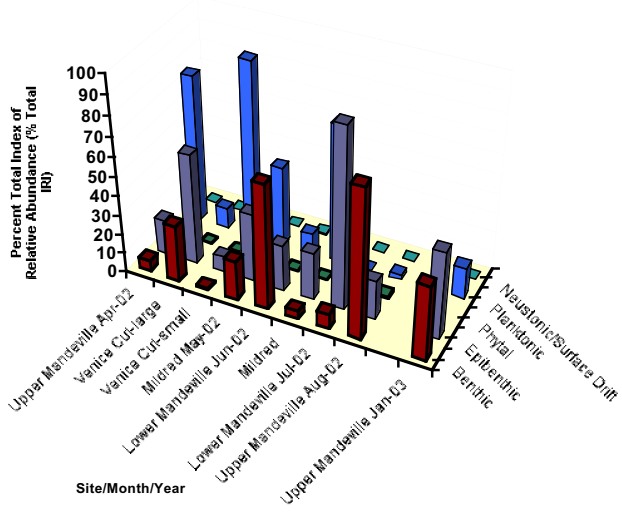


FIGURE 46. Variability in relative importance (%total IRI) of spectra of seven common fishes in the central Sacramento–San Joaquin River Delta, 1998–99 BREACH studies.







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WATER HYACINTH INFLUENCES

Introduction

The invasion of, water hyacinth (*Eichhornia crassipes*) has caused a hotbed of controversy over issues of control and management. By the 1980s, its abundance became a hindrance to boat traffic. Chemical control of water hyacinth currently has an annual cost of approximately $1,000,000 (P. Thalken, California Dep. Water Resources, Sacramento, pers. comm.). Biological invaders such as water hyacinth have become widespread on a global level. Exotic species can alter the population dynamics and community structure of native ecosystems, and are primarily successful in disturbed habitats. This is especially important in the Sacramento–San Joaquin Delta, as the San Francisco Bay area is considered the major estuary in the United States most modified by human activity (Nichols et al. 1986), and may be the most invaded estuary in the world (Cohen and Carlton 1998).

Research elsewhere in the world has shown that the roots of water hyacinth can be important habitat for epibenthic macroinvertebrates, mainly amphipods (Gopal 1987). Floating aquatic vegetation can also be beneficial as a nursery habitat for juvenile fishes, as well as many invertebrates. This is often dependent on patch size, as large patches of water hyacinth can cause low dissolved oxygen, high detritus production, and senescence of submerged vegetation (Gopal 1987). The effects of water hyacinth on community dynamics compared with its native functional counterparts has not been studied in the delta, and they have received little examination elsewhere. The native pennywort (*Hydrocotyle umbellata*) functionally occupies the same habitat as water hyacinth in the delta. It is expected that invertebrate taxa richness and density will be different between the two vegetation types owing to changes in the following:

1. spatial complexity of the vegetative structures (Figs. 71-73),
2. shading effects of dense canopies,
3. amount and location of plant biomass,
4. densities of vegetation patches,
5. plant detritus deposition rate,
6. growth rates,
7. dissolved oxygen levels, and
8. rates of evapotranspiration (Gopal 1987).

Effects on the fish/invertebrate predator–prey food web are particularly unknown, and are important because of the prominence of FAV as a major habitat zone in this food web.

Objectives

The objectives of this component of the study were as follows:

1. Characterize the assemblages of macroinvertebrates in

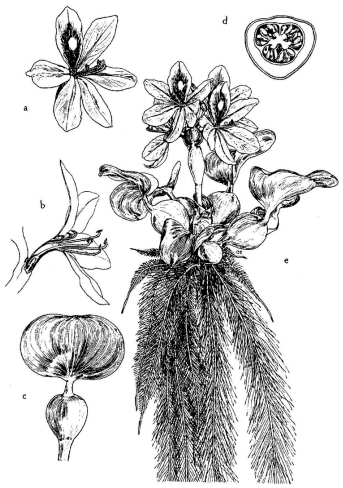

FIGURE 71. *Eichhornia crassipes*, water hyacinth.

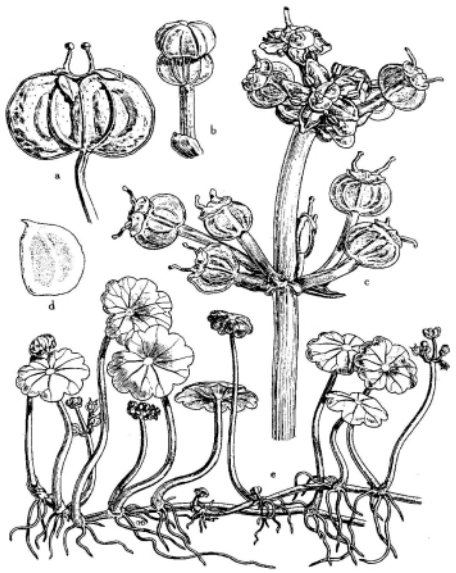

FIGURE 72. *Hydrocotyle umbellata*, pennywort.

FIGURE 73. Patch of *E. crassipes* along the marsh fringe.

the roots, benthic macroinvertebrates, and terrestrial insects associated with water hyacinth and pennywort.
2. Characterize the resident fish assemblages and food web pathways.
3. Characterize physical measurements of dissolved oxygen and patch size.

Methods

Study Sites

We are studying 3 sites in the delta, which are a subset of the 10 study sites involved in the BREACH research program (Fig. 74). Site A was sampled in June of 1998, and Sites B and C were sampled in August of 1998. All vegetation patches were located on the marsh fringe and were medium in size. Length and width measurements of the FAV canopy were taken at each patch. Sampling was conducted as follows:

1. Epibenthic invertebrates living in the root masses of the vegetation were sampled by manually collecting plant samples. Macroinvertebrates were then separated from the collected root mass by immersing the root mass into a bucket containing 10% ethanol. Canopy surface area was determined by correlating the number of leaves in each plant sample to the number of leaves in a 0.5-m^2 quadrat.
2. Benthic invertebrates were sampled with a 2-in-diameter core to a depth of 10 cm. Sampling was also conducted at nearby emergent tule (*Scirpus* sp.) and riparian patches when present.
3. Insect fallout traps were used to sample the terrestrial insects living in the vegetation canopies. These traps consisted of a rectangular tray (55-cm x 38-cm) filled with soapy water. The trays were tethered to PVC poles at each site, allowing vertical movement with the tides. The trays were collected after 24 hours after initial placement. Sampling was also conducted at nearby emergent tule (*Scirpus* sp.) and riparian patches when present.
4. Seine-netting was used to sample fish underneath FAV. Although not presented in this report, the California Department of Water Resources (CDWR) also is sampling fish in shallow water areas adjacent to FAV using seine-netting (see Fish subsection).

Fish were saved for diet analyses. Prey items were ranked based on modified IRI (Index of Relative Importance) values. Diet overlap with invertebrates is calculated using the PSI (Percent Similarity Index), with a value of 100 showing complete overlap.

Physical Sampling

Measurements of dissolved oxygen and patch size were taken at each FAV patch.

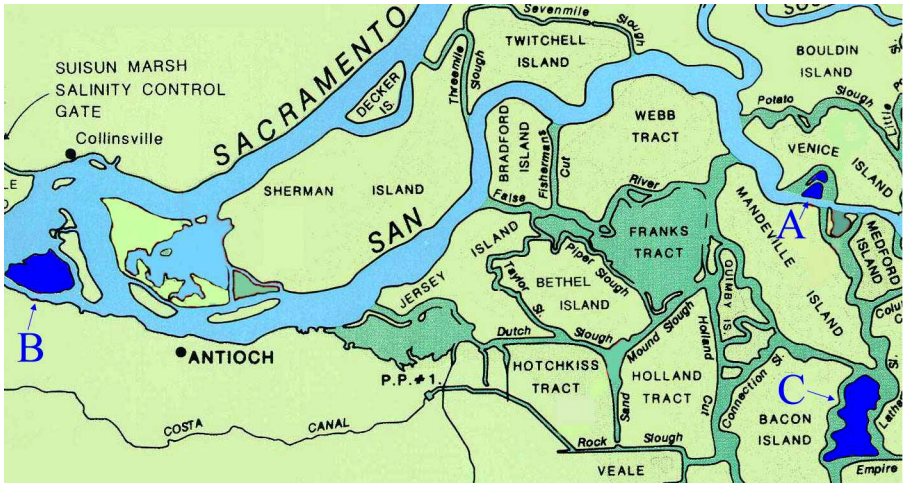

FIGURE 74. Study sites for assessment of water hyacinth effects of Delta food webs.

Preliminary Results and Discussion

Biological Sampling

Epibenthic Invertebrates in the Roots

The amphipods *Crangonyx floridanus*, *Hyalella azteca*, and *Gammarus daiberi*, and the isopod *Caecidotea racovitzai* are the most abundant taxa overall (Fig.75; see box for a description of amphipods and isopods, many of which are introduced, or first records for the delta, or both). Results are specific for each site and signify differences in invertebrate communities between water hyacinth and pennywort. For example, at Site A the major species is the introduced *C. floridanus* at hyacinth, and the native *H. azteca* at pennywort. Taxa richness and the Shannon-Weiner Diversity Index are higher for pennywort in June (Site A), but higher for hyacinth in August (Sites B and C; Table 6). This correlates with the peak bloom of pennywort in June, and the peak bloom of hyacinth in August.

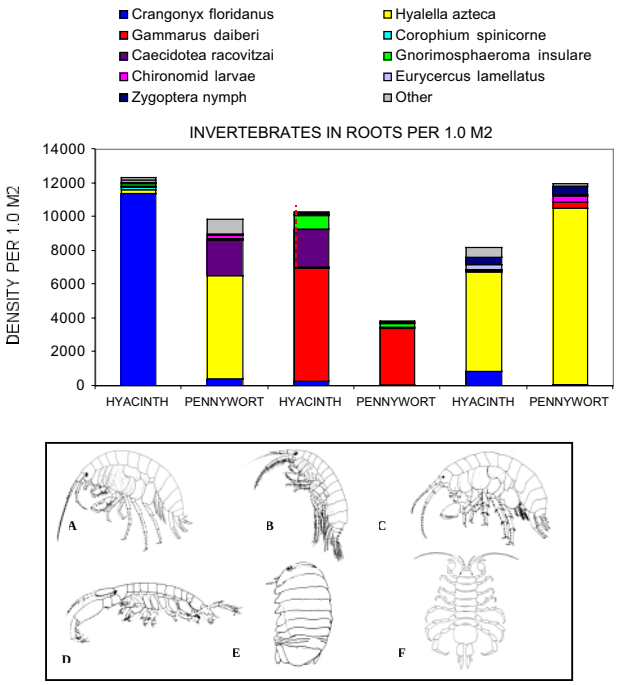

FIGURE 75. Density of root invertebrates at Sites A, B, and C (n=5); sampled amphipods (A-D) and isopods (E-F). A. *Crangonyx floridanus*, first record in the delta, introduced? B. *Gammarus daiberi*, introduced; C. *Hyalella azteca*, native; D. *Corophium spinicorne*, native; E. *Gnorimosphaeroma insulare*, native; F. *Caecidotea racovitzai*, first record in the delta, introduced? and *Caecidotea* sp. A, first record in the delta, characteristic of *Caecidotea hilgendorfii* from Asia, introduced?

Benthic Invertebrates

Oligochaetes represent the most abundant taxa overall (Fig. 76). In June (Site A), taxa richness and the Shannon-Weiner Diversity Index are much higher for FAV than for emergent and riparian strata (Table 6). However, in August (Site B), taxa richness in water hyacinth is equal to that for the emergent strata, while pennywort still has high values. This is presumably due to the high deposition rate of plant detritus associated with water hyacinth. Most of the additional taxa in the FAV represent fallout amphipods and isopods from the overlying root mass community.

Terrestrial Insects in the Vegetation Canopy

Chironomidae and Collembola represent the most abundant taxa overall for June (Fig. 77). The abundance of Cicadellidae in pennywort patches is the major difference with water hyacinths. Measurements of taxa richness and the Shannon-Weiner Diversity Index are similar for FAV, and both are higher than emergent and riparian strata (Table 6).

Fish

Numbers and average lengths for all fish captured in five seine-net samples underneath five separate patches of

TABLE 6. Measurements of taxa richness and the Shannon-Weiner Diversity Index for representative invertebrate sampling.

	Taxa richness	Shannon-Weiner Diversity Index
Root invertebrates		
Hyacinth A	26	1.04
Pennywort A	28	2.34
Hyacinth B	20	1.65
Pennywort B	16	1.18
Hyacinth C	21	2.00
Pennywort C	20	1.02
Insects		
Hyacinth A	24	2.29
Pennywort A	25	2.12
Emergent A	19	1.14
Riparian A	18	1.7
Benthic invertebrates		
Hyacinth A	16	2.61
Pennywort A	13	1.92
Emergent A	7	0.25
Riparian A	8	0.88
Hyacinth B	5	0.26
Pennywort B	12	1.47
Emergent B	4	0.31

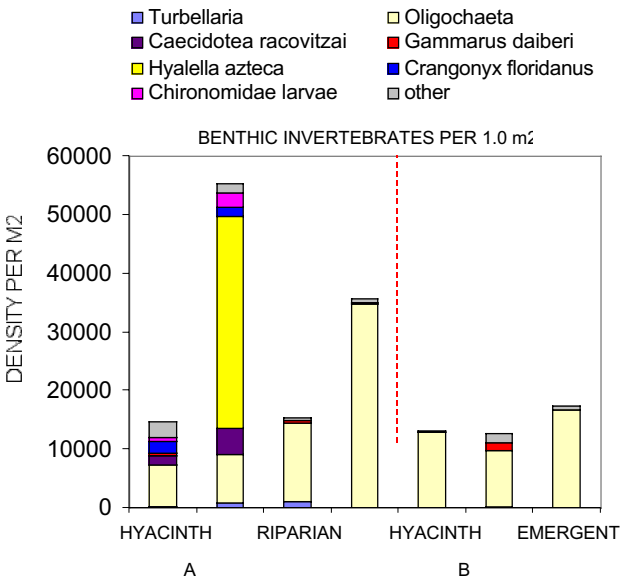

FIGURE 76. Density of benthic invertebrates at Sites A and B (n=5).

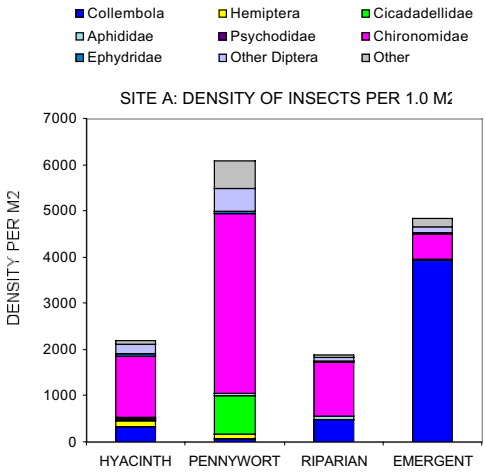

FIGURE 77. Density of insects at Site A(n = 5 for hyacinth and emergent, n = 4 for pennywort and riparian).

water hyacinth at site C are as follows: six juvenile bluegill, 75.83 mm; 24 small juvenile bluegill, 25.25 mm;18 juvenile largemouth bass, 51.89 mm; 5 rainwater killifish (*Luciana parva*), 28.80; and 2 brown bullhead (*Ictalurus nebulosus*), 35.0 mm. All these fish are non-native to the delta. Other common taxa included the crayfish *Procambarus clarkii* and the giant water bug *Belostomatidae*. Figure 78 illustrates a representative IRI for bluegill (*Macrochirus lepomis*). A PSI value of 64.36 with prey invertebrates in the root mass shows that these fish are feeding mainly on the amphipods, isopods, zygoptera nymphs, and Chironomidae larvae in the over-

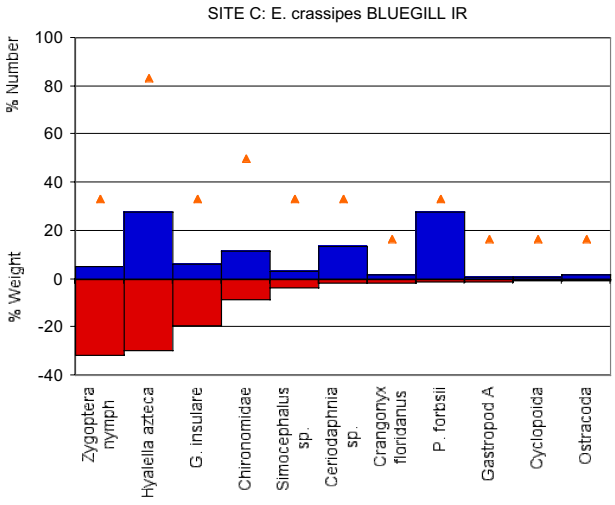

FIGURE 78. IRI of bluegill fish prey. Triangles represent % frequency of occurrence.

lying root mass. The remainder of the prey comprises planktonic copepods, cladocerans, and ostracods. Site C was the only site sampled in this manner as the water was too deep at all other sites. However, sampling by CDWR in shallow-water areas adjacent to the FAV patches has produced additional fish data. Diet analyses on these samples illustrate similar trends in prey foraging.

Physical Sampling

At site B, dissolved oxygen levels are significantly lower underneath both FAV patches than at emergent strata, with water hyacinth having a slightly lower value than pennywort. At site C, water hyacinth has a lower value than emergent strata, but pennywort has a much higher value. This could again be due to the high deposition rate of plant detritus associated with water hyacinth. Average FAV patch area for all sites was 30.26 m^2, except for the pennywort patches at Site A, which meandered along the marsh edge and did not have a strictly defined boundary.

Summary

Apparently, water hyacinth has had a remarkable impact on nearshore habitats in the Sacramento–San Joaquin Delta, as well as many other areas throughout the world. The invertebrate communities associated with water hyacinth are often unique from the native pennywort. The invertebrates living in the root mass serve as prey for resident non-native fish. These root mass invertebrates consist mostly of amphipods and isopods, many of which are introduced. It is debatable whether some of these crustaceans

may have arrived into the delta via the roots of water hyacinths. All fish sampled underneath canopies of water hyacinth were juveniles, so it appears that fish use water hyacinth as both a refuge habitat and food resource. water hyacinth can have a detrimental effect on the underlying benthic community as compared to pennywort because of high deposition rate of plant detritus and low dissolved oxygen levels. Congruent with the high monetary value placed on controlling the spread of water hyacinths, such preliminary findings warrant more research on the role of water hyacinth in the nearshore community.

PRELIMINARY INTERPRETATIONS

These preliminary results provide some intriguing interpretations to the intent and process of restoring delta wetlands by breaching levees:

- The process of rebuilding intertidal elevations, which will be readily colonized by emergent marsh vegetation, cannot be directly extrapolated from what we know about the historical formation of the delta and depends greatly on the extent of leveed-island subsidence and the geomorphic region of the delta. On the basis of our independent estimates from feldspar, SET, ^{210}Pb, and core stratigraphy, we suggest that about 4 cm yr^{-1} might be predicted for subtidal habitats, and about 1 cm yr^{-1} for intertidal habitats, depending largely on the extent of wave and current energy. Intervention through enhanced sediment input (dredge material disposal) offers one of the few mechanisms of shortening the subtidal/FAV habitat phase.
- Native tule marsh vegetation will rapidly colonize emerging intertidal elevations but submerged and floating aquatic vegetation, including introduced species such as water hyacinth and parrots feather, will dominate subtidal habitats. We are uncertain what the role of aquatic vegetation is in affecting the process of transcending from subtidal to intertidal elevations.
- The occurrence and density of introduced fishes likely will continue to exceed native fishes even with increased levee-breach restoration owing to the extensive area and duration of the subtidal-SAV/FAV phase of the restoration process and the ability of introduced fishes to exploit these habitats for a greater proportion of the year. The preponderance of native fishes appears during the winter and early spring when water temperatures are at their lowest.
- Maximum invertebrate density typically occurs at the reference site, suggesting the mature site is potentially more productive. Because composition of benthic macroinvertebrate and fallout insect assemblages in breached-dike shallow-water habitats are generally similar to reference sites, breached-dike restoration sites should rapidly contribute to the delta's emergent wetland secondary production.
- Our preliminary findings that emergent marsh and SAV/FAV habitats demonstrate distinct differences in terms of benthic macroinvertebrate and insect contributions suggest implicit ecological "trade-offs" to restoration strategies that promote large areas and long periods of the subtidal habitat phase of restoration.
- Evidence that food webs supporting both native and introduced fishes derive from SAV/FAV as well as emergent marsh habitats imply that, although SAV/FAV (including exotic species) habitats support prey resources of many fishes, more opportunistic fishes would benefit from early restoration phases while more restricted habitat/food web specialists will benefit from later stages of predominantly intertidal habitats.

REFERENCES

Aronson, J., and E. Le Floc'h. 1996. Vital landscape attributes: Missing tools for restoration ecology. Restor. Ecol. 4:377-387.

Atwater, B. F. 1980. Attempts to correlate late Quaternary climatic records between San Francisco Bay, the Sacramento–San Joaquin Delta, and the Mokelumne River, California. Ph.D. dissertation, Univ. Delaware. 212 pp + maps.

Atwater, B.F. April 1980. Distribution of vascular-plant species in six remnants of intertidal wetland of the Sacramento - San Joaquin Delta, California. U.S. Geological Survey Open-File Report 80-883. Preliminary report.

Atwater, B.F. 1982. Geologic Maps of the Sacramento-San Joaquin Delta, California, U.S. Geological Survey MF-1401, Menlo Park, CA.

Atwater, B. F. and D.F. Belknap. 1980. Tidal Wetland Deposits of the Sacramento–San Joaquin Delta, California. *In* M.E. Field, A.H. Bouma, I.P. Colburn, R.G. Douglas, and J.C. Ingle (eds.), Quaternary Depositional Environments of the Pacific Coast. Pacific Coast Paleogeography Symposium 4.

Atwater, B.F., S.G. Conard, J.N. Dowden, C.W. Hedel, R.L. MacDonald, and W. Savage. 1979. "History, Landforms, and Vegetation of the Estuary's Tidal Marshes." *In* T.J. Conomos, A.E. Leviton, and M. Berson (eds.), San Francisco Bay: the Urbanized Estuary; Investigations into the Natural History of San Francisco Bay and Delta with Reference to the Influence of Man. Fifty-eighth annual meeting of the Pacific Division/American Association for the Advancement of Science held as San Francisco State University, San Francisco, California, June 12-16, 1977.

Boumans, R. M., and J. W. Day. 1994. Effects of two Louisiana marsh management plans on water and material flux and short term sedimentation. Wetlands 14:247-261.

Cahoon, D., D. J. Reed, and J. W. day. 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and arghoorn revisited. Mar. Geol. 128:1-9.

California Department of Water Resources (CDWR). 1995. Sacramento San Joaquin Delta Atlas.

California Department of Water Resources (CDWR). August 1980. Subsidence of Organic Soils in the Sacramento-San Joaquin Delta. Central District.

California Department of Water Resources (CDWR). December 1982. Delta Levees Investigation. Bulletin 192-82.

Cohen, A.N. and J.T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. Science 279:555-558.

Cosby, S.W. 1941. Soil Survey of the Sacramento-San Joaquin Delta Area, California. U.S. Department of Agriculture. Bureau of Chemistry and soils. Series 1935, no.21.

Fox, P. 1996. Memorandum to E. Archibald, G. Bardini, G. Chan, S. Kramer, B.J. Miller, and J. Monroe, re: Delta Shallow Water Habitat. May 7.

Gopal, B. 1987. Aquatic Plant Studies 1. Water Hyacinth. Elsevier Publishing.

Matthew, R., J.A. Chase, and D.R. Warren. 1931. Variation and Control of Salinity in the Sacramento- San Joaquin Delta and Upper San Francisco Bay. California Department of Water Resources Bulletin No. 27, Sacramento, CA.

May, M.D. 1999. Vegetation and salinity changes over the last 2000 years at two islands in the northern San Francisco Estuary, California. Master thesis. University of California at Berkeley, Department of Geography.

National Geodetic Survey. 1998. National Geodetic Survey tidal benchmark data sheets. Web page: *www.opsd.nos.noaa.gov/bench/ben.ca.html*.

National Oceanic and Atmospheric Administration (NOAA). 1998. California Sacramento and San Joaquin Rivers. Nautical chart 18661, 24th edition. U.S. Department of Commerce.

Nichols, M.N. and J.D. Boon. 1994. Sediment Transport Processes in Coastal Lagoons. In Coastal Lagoon Processes edited by B. Kjerfve. Elsevier Oceanography Series, 60.

Nichols, F.H., J.E. Cloern, S.N. Luoma, and D.H. Peterson. 1986. The modification of an estuary. Science 231:567-573.

Philip Williams & Associates (PWA). February 23, 1999. Memorandum from Philip Williams and Michelle Orr, PWA, to Terri Nevins, California State Coastal Conservancy, re: Re-evaluation of the Internal Peninsula Design in the Hamilton Wetlands Restoration Plan.

Philip Williams & Associates (PWA), Pacific Estuarine Research Lab, Louisiana Universities Marine Consortium, and William Lettis and Associates. January 1995. Design Guidelines for Tidal Channels in Coastal Wetlands. Prepared for the U.S. Army Corps of Engineers Waterways Experiment Station. PWA Report #867.

San Francisco Estuary Project (SFEP). 1991. Status and Trends Report on Wetlands and Related Habitats in the San Francisco Estuary. Prepared by the Association of Bay Area Governments, Oakland, CA. December.

Simenstad, C. A., and R. M. Thom. 1996. Assessing functional equivalency of habitat and food web support in a restored estuarine wetland. Ecol. Appl. 6:38-56.

Thompson, J. 1958. The Settlement Geography of the Sacramento-San Joaquin Delta, California. Doctoral Dissertation, Sanford University, Stanford, CA.

Toft, J. 2000. Community effects of the non-indigenous aquatic plant water hyacinth (*Eichhornia crassipes*) in the Sacramento/San Joaquin Delta, California. M.S. thesis, Univ. Washington, Seattle.

U.S. Coast and Geodetic Survey. 1867. Hydrography of part of Sacramento and San Joaquin Rivers, California by the party of Edward Cordell. Scale 1:10,000. Map (register) number 935.

USDA (U.S. Department of Agriculture). 1913. Sacramento Valley Reconnaissance Soil Survey, California.

USDA. 1937. Agricultural Adjustment Administration. 1937 aerial photographs of Solono, Sacramento, and San Joaquin counties. October.

U.S. Fish and Wildlife Service Sacramento (USFWS) and U.S. Army Corps of Engineers Sacramento District (USACE). 1990. Design and Biological Monitoring of Wetland and Riparian Habitats Created with Dredged Materials, Deep Water Ship Channel Monitoring Program.