COMPARING ZOOPLANKTON AND SNAIL DENSITIES AMONG REFERENCE AND RESTORED MARSHES

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By Cheryl L. Davis
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COMPARING ZOOPLANKTON AND SNAIL DENSITIES AMONG REFERENCE AND RESTORED MARSHES

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Preface to Thesis: Importance of Wetlands

In many parts of the world, wetlands are a major feature of the landscape. They are not merely ecotones between terrestrial and aquatic environments but they are ecosystems themselves, sharing characteristics of deepwater systems (algae, bottom-dwelling invertebrates, swimming animals, drifting animals, water movement and anoxic substrate) as well as vascular plant flora analogous to plants found in uplands (Mitsch and Gosselink 2000, National Resources Council 1992).

Wetlands also serve an important function in mitigating floods, stabilizing water supplies and as filters for natural and manmade waste. Additionally, they provide unique habitats for a wide variety of plants and animals (Mitsch and Gosselink 2000, NRC 1992). According to the Council on Environmental Quality (1989), wetlands are essential in providing food, cover and freedom from disturbance as well as other essential habitat factors. Over one-half of all saltwater fish and shellfish harvested annually in the United States, as well as most freshwater game fish, use wetlands for feeding areas, spawning grounds, and nurseries for young. Approximately one-third of North American bird species are associated with wetlands not only as resident birds year-round but also as breeding, feeding and overwintering areas (CEQ 1989).

Wetlands previously have been misunderstood and deemed "wastelands" that needed to be reclaimed (generally for agricultural purposes; NRC 1992). The most destructive alteration of wetland areas has been physical, generally eliminating the topography and hydrology, which supports a wetland ecosystem (NRC 1992). Prior to the mid 1970s, destruction of wetlands was accepted and even encouraged by several United States.
government policies, specifically the Swamplands Act of 1849, 1850, and 1860 which encouraged 15 states along the Mississippi to Oregon to reclaim any wetlands areas for agriculture (NRC 1992). Since the mid-1800s more than one-half of the United States original wetlands have been drained (NRC 1992).

Loss of wetland habitat has been most acute in California where approximately 91% of all wetland habitats have been diked, dredged or filled (Dahl 1990). This destruction represents the highest percentage loss of wetlands in the United States, as approximately 5,000,000 acres of wetlands were present in the 1780s and 1980 left 454,000 acres or 183,700 hectares of wetlands. Florida suffered the greatest actual loss of acres, 9,286,713 acres or 3,759,800 hectares (Dahl 1990).

National wetland conservation efforts began as early as the 1930s through such programs as the duck stamp program and continue today through the work of such organizations as the Ducks Unlimited, the Nature Conservancy, the Pacific Estuarine Research Lab in San Diego, California, and the Society of Wetlands Scientists (Mitsch and Gosselink 2000).

In 1988 the National Wetlands Policy Forum was created to raise political and public awareness of the problem of wetlands destruction and this group put forth the “no net loss” of wetlands policy (Mitsch and Gosselink 2000). In 1992 the National Research Council set a goal to gain, primarily through reconversion of crop and pastureland, 4,000,000 hectares of wetland habitat in the United States by 2010 (NRC 1992, Mitsch and Gosselink 2000).
The ecological problems of the San Francisco Estuary have national and international importance because much of the damage to this ecosystem has also occurred in the world’s other urbanized estuaries. The Sacramento and San Joaquin rivers drain California’s Central Valley, which is approximately 40 percent of the land area of California. These rivers empty into a 3,000-km² delta (historically marsh area). The estuary itself has a surface area of 1,240 km² (San Francisco Estuary Project, 1990).

Since the mid-nineteenth century, one-third of San Francisco Bay has been filled (converted to dry land), 95% of the bay’s tidal marshes have been dredged, filled, or diked and approximately 60% of its freshwater inflow has been diverted for agriculture purposes (NRC 1992, Josselyn 1983). This great reduction of freshwater accompanied by the gradual introduction of toxic chemicals nearly depleted the formerly abundant fishery by 1950; in 1875 this bay region supplied 93% of the state’s commercial fish. (Skinner 1962, NCR 1992).

Numerous marsh restoration projects have been implemented for San Francisco Bay (Berger 1990) and in Southern California (Zedler 1994). However, restoration ecology is a relatively new science and there is a lack of knowledge as ecosystems are difficult to restore to include many components and support complex interactions (Zedler 2000).

Site to site variability is high, and trading one site for another (environmental mitigation) is a difficult prospect with an unproven track record. Tidal marsh restoration in Southern California has suggested that the trajectory (recolonization) of a restoration site is not straight and is highly unpredictable (Zedler 1999).
Even given these challenges, marsh restoration is predicted to be most successful if the site has not been drastically altered (NRC 1992, Zedler 2000). Many of the diked tidal marsh areas of San Francisco Bay retain some marsh characteristics such as elevation (Josselyn 1983). The restored brackish marshes of the San Francisco Estuary presented in this paper were such marshes as the general topography and elevation of the sites had not been greatly altered. However, the hydrology of these marshes (within Southern Suisuin Bay and one marsh in San Pablo Bay, each in northern San Francisco Estuary) had been altered by erecting tidal gates (to block tidal action) and by creating dikes, primarily to provide ponds for waterfowl hunting. Habitat restoration in these cases involved either the removal or dismantling of a tidal-gate or cutting through levees, which formerly blocked tidal amplitude, thus restoring various degrees of tidal amplitude and access to fishes and other aquatic animals.

This restoration effort occurred under the banner of CALFED, an alliance of local, federal, and state governments and university researchers. The primary goal of this restoration project was to restore juvenile fish habitat. Overall, physical factors (salinity, secchi depth, and water clarity, etc.), fish, benthic invertebrates and zooplankton were monitored for approximately 3 years. Other factors possibly influencing animal abundance were noted, such as tidal pools, channels and tidal amplitude.

Data analyzed from the monitoring of these restoration sites included comparing densities of aquatic animals among restored and reference/historical marshes (old marshes that have not been altered directly) and in this phase, correlating zooplankton densities with additional data on fish densities. The data and conclusions from this study
not only add to the growing body of research in marsh restoration but also can provide valuable information that can improve future restoration efforts.

Literature Cited in Preface:


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Chapter 1

COMPARING ZOOPLANKTON DENSITIES AMONG REFERENCE AND
RESTORED MARSHES IN UPPER SAN FRANCISCO BAY ESTUARY,
CENTRAL CALIFORNIA

ABSTRACT
Significant loss of wetland habitat with the subsequent loss of suitable habitat for juvenile fish in the San Francisco Estuary has led state and federal agencies along with university researchers to unite in the CALFED Bay Delta Program, which has restored several previously non-tidal marshes in the Estuary to various degrees of tidal amplitude. Hypothetically, reference/historical marshes that have not been diked, dredged or filled should yield greater zooplankton densities (a primary source of food for juvenile fish) compared to marshes recently restored to tidal action. This study examines the hypothesis by comparing zooplankton population densities among reference and restored marshes and testing for a correlation between increased zooplankton densities and increased fish densities within the marshes. Zooplankton sampling occurred approximately monthly (not all sites were accessible each month) at two major reference sites (Edith West Reference Marsh and Statelands Reference Marsh) and at six restored sites (Inner McNabney/Shell Marsh, Outer McNabney/Shell Marsh, Waterfront Marsh, Pt. Edith Marsh, Navy Marsh, all in southern Suisun Bay, and Tubbs Island Marsh in San Pablo Bay). Limited zooplankton sampling was also conducted at two additional reference marshes 10 km up the Delta from Suisun Bay (Northern Brown’s Island Marsh
and Sherman Island Marsh). At each marsh, zooplankton samples were obtained near the entrance of the tidal channel. The hypothesis of higher reference marsh zooplankton densities was rejected for several marshes with tidal pools connected to the tidal channels; these marshes yielded significantly higher zooplankton densities than the reference marshes. Magnitude of the mean differences ranged from 300-1000%.

Furthermore, increased zooplankton densities in these restored marshes with connected tidal pools correlated with increased densities of small fishes. However, two restored marshes lacking tidal pools and one marsh with a small tidal pool yielded significantly lower overall zooplankton densities when compared to the reference marshes though the magnitude of differences in the mean were small (approximately 1-3%). Both additional reference marshes further up the Delta (Northern Brown’s Island, and Sherman Island) yielded low zooplankton densities similar to that of the original reference marshes.

Additionally, other researchers involved in our CALFED study noted reference marshes and restored marshes lacking tidal pools yielded fewer fish and epibenthic animals (amphipods, cumaceans, isopods, etc.) than did the marshes with tidal pools connected to the tidal channels. Generally, calanoid copepods were the predominant taxa at all sites and other taxonomic lists were fairly similar among the reference and restored marsh sites. Since restoration is a relatively new area of study, restoration efforts should proceed cautiously with restoration plans tailored to meet the unique environmental conditions present at each site. Conservation of existing sites (sites that have not been dredged, diked or filled) should be the focus with restoration as an experimental alternative solution. However, because there are few marsh habitats left to conserve in
the San Francisco Bay Estuary, and these results are encouraging even for restoration to partial tidal action, it is likely that restoration efforts will continue and improve at future sites.

INTRODUCTION

Approximately 91% of all historical wetland habitats in California have been diked, dredged or filled for agriculture, urbanization, and other human activities (Dahl 1990). Loss of tidal marshes has been particularly acute in the San Francisco Estuary due to high-densities of human populations in this area. Approximately 95% of tidal marshes in the San Francisco Estuary have also been diked, dredged or filled (Josselyn 1983).

With little marsh habitat left to conserve, the focus of state and federal agencies has been restoration efforts (Berger 1990, Zedler 1994). The CALFED project, a collaboration of state and federal agencies in collaboration with university researchers, has restored several marsh sites in the San Francisco Estuary to tidal action (Fig. 1).

The overall hypothesis of this project is that historical marshes (marshes that have not been diked, dredged, or filled) and restoration marshes will yield different population densities of aquatic animals, and that colonization of restored marshes will improve through time if conditions are suitable (Kitting 2001, Kitting et al 2001). A related hypothesis was that historical/reference marshes would have higher population densities of fishes and invertebrates than restored marshes (Zedler 1999, Kitting et al 2001). So far this hypothesis has been clearly rejected in several restored marshes as these marshes
yielded significantly greater densities of epibenthic invertebrates and fish (Kitting et al. 2001).

This paper focuses on the comparison of zooplankton densities among two major reference marshes and six marshes restored to various degrees of tidal action. The goal is to test the hypothesis using only zooplankton population density data.

The zooplankton assemblage has potential for consideration as an additional assemblage for wetland bioassessment, particularly because zooplankton are valuable resources for larval fish (Dodson 2001, McGinnis 1984, Moyle 2002). The presence/absence of high zooplankton densities could be used as an indicator of the suitability for other species, particularly larval fish species (Dodson 2001).

During the years of 1999-2001, zooplankton densities in reference marshes were compared to zooplankton densities in restored marshes (marshes restored to tidal action), taking into account such factors as tidal amplitude, marsh tidal pools, and various physical factors (water temperature, salinity, water clarity). Higher densities of zooplankton were expected in the reference marshes, which had not been degraded (marshes that had remained in a relatively natural state for approximately 200 years) compared with zooplankton densities in marshes that had been cut off from tidal action. Zooplankton densities in some pristine marshes are as high as 27,000 aquatic invertebrates per m³ (Huh and Kitting 1985). Loss of tidal action would degrade the habitat for almost all species dependent on the marsh, but particularly for aquatic species that normally move in and out of a marsh during their life cycle.
Marshes restored to tidal amplitude are Inner McNabney/Shell, Outer McNabney/Shell, Waterfront, Pt. Edith, and Navy (all located in southern Suisun Bay), and Tubbs Island Muted Marsh in San Pablo Bay, Sonoma County (Fig. 1, 2).

The two McNabney/Shell marsh sites are micro-tidal, receiving tidal amplitude of approximately 0.25 m from leaking tidal gates (structures that close off a marsh to tidal amplitude). These two marshes are the most altered sites due to micro-tidal amplitude and a daily input of high quality waste-water, which enters approximately between the two marsh sites. Outer McNabney/Shell Marsh is located at the bayward end of these two connected marshes, approximately 1 km from the opening of the tidal channel to Southern Suisun Bay and is approximately 2 km². Inner McNabney/Shell Marsh is located near the landward end of the marsh approximately 1.5 km from the opening of the tidal channel and is approximately 1 km². This latter marsh has the largest, typically deepest marsh tidal pools of all of the marshes in the study (Table 1).

Navy Marsh and Pt. Edith Marsh are restored to approximately full tidal amplitude of 1.9 m with deep inner tidal channels connected to Southern Suisun Bay. Navy and Pt. Edith marshes have similar, linear configurations, each marsh occupying approximately 1 linear km. Waterfront Marsh is restored to tidal amplitude of approximately 1.0 m and receives tidal action from an historic slough. Waterfront shares the linear configuration of Navy Marsh and Pt. Edith Marsh occupying approximately 1 linear km (Table 1).

Tubbs Island Marsh is the more saline marsh located on San Pablo Bay. This marsh is approximately 2 km². During the years of the study, the Tubbs Island Marsh site
experienced sudden shifts in salinity (within approximately a month’s time) due to silting in of the channel to the marsh from Tolay Creek, which feeds the marsh (Fig. 1).

Edith West Reference Marsh and Statelands Reference Marsh are fully tidal at 2.1 m, with deep channels connected to Southern Suisun Bay. These marshes also share a linear configuration with each other and the above mentioned restored marsh sites (Navy, Pt. Edith and Waterfront) but they are longer, each occupying approximately 2 linear km. The McNabney/Shell marshes, Tubbs Island Marsh, and Waterfront Marsh all have marsh tidal pools connected to tidal channels (Table 1).

METHODS

The reference and restored marshes in southern Suisun Bay are located at 38 degrees 2.5' N, 122 degrees 4.4' W and are defined as brackish marshes, in the salinity range of 2-20 ppt. Tubbs Island Marsh is located on San Pablo Bay in Sonoma County at 38 degrees 7.3' N, 122 degrees 26.5' W.

Zooplankton sampling occurred approximately monthly at all reference and restored sites, at high tide or soon thereafter (slight ebb). Not all sites were accessible each month of the study. Zooplankton sampling was conducted with 250-micron mesh plankton nets with a 25 cm inside diameter. The zooplankton net was thrown out >10 m along the shore and then pulled back with the aperture of the net completely submerged under water for 10 m. Four replicates, each one representing a 0.25-m³-zooplankton sample, were taken at each marsh where the tidal channel enters the marsh. The four replicates yielded zooplankton per m³. Samples were immediately fixed with ethanol in 120-ml sample
cups, counting was conducted under a dissecting scope using low power, and each taxon with over 300 individuals was sub-sampled to 10% of the original sample. Data were entered on an Excel database located at California State University, Hayward, California, by the author and was provided to CALFED by Dr. Chris Kitting (Kitting et al. 2001).

Since not all sites received monthly sampling, the population densities were calculated as seasonal averages. Seasons were defined as winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). The ancient marshes of Brown’s Island and Sherman’s Island were only sampled twice, winter 2001 and fall 2002. The Brown’s Island Marsh is located at 38 degrees 2.6’ N, 121 degrees 52’ W and Sherman’s Island Marsh is located at 38 degrees 2.5’ N, 121 degrees 50’ W.

Data Analysis

All data were tested for normality and homogeneity of variance using the Kolmogorov-Smirnov and Levene’s test. Both physical and biological factors did not comply with the assumption of homogeneity of variance and non-parametric tests were used for analyses. The Kruskal-Wallis test was used to assess differences in physical factors and zooplankton densities among reference and restored marshes and the impact of marsh tidal pools on increased zooplankton densities. The Mann-Whitney U-test was used to assess differences in physical factors between individual sites and differences in seasonal and yearly zooplankton densities at each site. The Spearman’s Correlation test was used to ascertain if overall juvenile and small fish densities were correlated with
RESULTS

Physical Factors Comparisons

Salinity varied among the reference and restored marshes between 1999-2001 but salinities were statistically significantly different overall between the sites (Kruskal-Wallis, Chi$^2 = 67, 7$ df, $p < 0.001$). Compared to the other marshes, micro-tidal Inner McNabney/Shell and Outer McNabney/Shell Marshes had significantly lower overall salinities throughout the study (Mann-Whitney U-test). In these pair wise marsh comparisons, the greatest $U$ was 245, corrected for ties, and $p < 0.005$ for all marshes compared against these two sites. Additionally, Inner McNabney/Shell Marsh had significantly lower salinity than Outer McNabney/Shell Marsh (Mann-Whitney $U = 273$, $Z = -2.1$, $p = 0.032$; Fig. 3).

Tubbs Island experienced sudden shifts in salinity during the study. In summer 1999 salinity increased to 46 ppt. within a month. In spring 2000 salinities fluctuated between 6.7 – 25.2 ppt., and salinities reached 29.5 and 32.1 during the winter 2000-2001 sampling period. As noted, these shifts were due to silting of the channel feeding the marsh.
There were also significant differences in secchi depth, or water clarity, among the sites (Kruskal-Wallis: \( \chi^2 = 18, 7 \text{ df}, p = 0.012 \)). Pair wise comparisons revealed that Inner McNabney/Shell Marsh had significantly less water clarity (lower average secchi depths) than the other marshes (greatest Mann-Whitney \( U = 135 \), corrected for ties, and \( p < 0.032 \) for all comparisons) except for Tubbs Island Marsh which did not differ significantly from Inner McNabney/Shell (Fig.). Water temperature (Celsius) was comparable among the sites during the study (Fig. 3).

**Overall Zooplankton Densities Among Reference and Restored Marshes**

The reference marshes (Edith West and Statelands) had very low average densities of zooplankton overall at the end of the study, < 100 average zooplankton per 0.25 m\(^3\), compared to the three most abundant marshes: Inner McNabney/Shell Marsh, Tubbs Island Marsh, and Outer McNabney/Shell Marsh, which yielded overall average zooplankton densities of 33, 500, 18, 700, and 9, 900 per m\(^3\) respectively (Fig. 4). The other restored marshes, Waterfront, Navy and Pt. Edith, had overall zooplankton densities similar to those of the reference marshes, < 400 zooplankton per m\(^3\) (Fig. 4).

Zooplankton densities differed significantly among reference and restored marshes, (Kruskal-Wallis: \( \chi^2 = 163, 7 \text{ df}, p < 0.001 \)). Overall, Inner McNabney/Shell Marsh yielded significantly higher zooplankton densities than both Edith West Reference Marsh (Mann-Whitney \( U = 83 \), corrected for ties, \( Z = -8.5, p = 0.001 \)) and Statelands Reference Marsh (U = 139, corrected for ties, \( Z = -7.7, p < 0.001 \)). Tubbs Island Marsh had the second most abundant zooplankton overall and also had zooplankton densities significantly higher than both reference marshes (Edith West and Statelands) (Mann-
Whitney $U = 852$, corrected for ties, $Z = -3.61$, $p = .001$ and $U = 929$, corrected for ties, $Z = -2.2$, $p = 0.028$). Outer McNabney/Shell Marsh had the third most abundant zooplankton overall and this site also yielded zooplankton densities significantly greater than at the reference sites (Edith West and Statelands) (Mann-Whitney $U = 840$, corrected for ties, $Z = -5.5$, $p = 0.001$ and $U = 979$, corrected for ties, $Z = -4.0$, $p < 0.001$).

The Statelands Reference Marsh had statistically significantly greater zooplankton densities compared to the remaining restored marshes Pt. Edith Marsh, Navy Marsh, and Waterfront Marsh, (Mann-Whitney $U = 800$, corrected for ties, $Z = -2.3$, $p = 0.021$; $U = 261$, corrected for ties, $Z = -4.3$, $p < 0.001$; and $U = 334$, corrected for ties $Z = -2.8$, $p = 0.006$).

However, mean differences between Statelands Reference Marsh and these restored marshes were low, and differences among these three restored marshes were <50 zooplankton per 0.25 m$^3$ (approximately 1-3% difference) at each site. However, mean differences between the reference sites and the three most zooplankton-populated (restored) sites (Inner McNabney/Shell Marsh, Tubbs Island Marsh, and Outer McNabney/Shell Marsh) ranged from a low mean difference of 2,397 zooplankton per 0.25 m$^3$ (approximately 300 %) to a high mean difference of 8,086 zooplankton per 0.25 m$^3$ (approximately 1,000 %; Table 2).

The ancient marshes (~1,000 years old) at Brown’s Island and Sherman’s Island further up the Delta from Southern Suisun Bay also yielded low densities of zooplankton the two times they were sampled, <100 zooplankton per 0.25 m$^3$. 
Seasonal and Yearly Density Comparisons Among Reference and Restored Marshes

Average seasonal zooplankton densities were grouped into seven taxa (copepods, cladocerans, cumaceans, boatman, amphipods, mysids, and small fishes). The eighth category, "misc.,” consisted of all other zooplankton taxa, which occurred in low or very low densities (commonly 2-10 animals per 0.25 m\(^3\)). This category was represented by aquatic insect larvae, rotifers, isopods, additional adult insects, crab zoea, etc.

Though variability was high among seasons, years and sometimes samples at the marshes (Outer McNabney/Shell Marsh had an average monthly sample of 15, 879 animals per 0.25 m\(^3\) in July 2000 and an average monthly sample of 0.75 animals per 0.25 m\(^3\) in August 2000), the two reference marshes (Edith West Reference and Statelands Reference) had very low average seasonal densities of zooplankton during the years of the study (<250 zooplankton per 0.25 m\(^3\) sample in all seasons) when compared to several other marshes (Figs. 5, 6).

However, average seasonal zooplankton densities at the three most abundant (restored) marshes, Inner McNabney/Shell, Outer McNabney/Shell, in southern Suisun Bay, and Tubbs Island in San Pablo Bay, often exceeded \(10^3\) zooplankton per 0.25 m\(^3\) (Figs.7, 8, 9). Because of their micro-tidal nature (even with the daily input of reclaimed wastewater) both Inner Mc/Nabney Shell Marsh and Outer McNabney/Shell Marsh were subject to seasonal algal blooms with eutrophication, generally in the very dry late summer and early fall months.

Due to high zooplankton densities, both Inner McNabney/Shell Marsh and Tubbs Island Marsh are represented with scales of 0-18,000 zooplankton per 0.25 m\(^3\), while the
scale for Outer McNabney/Shell Marsh is one half this scale, 0-9,000 zooplankton per 0.25 m$^3$.

Of the three most abundant restored marshes (for most seasons), Inner McNabney/Shell yielded the greatest average seasonal densities of zooplankton by the end of the study. The highest seasonal average ($\pm$ std error) at this site was 15,350 $\pm$ 1,020 zooplankton (mostly copepods) per 0.25 m$^3$ in spring 2000 (Fig. 7). However, the most abundant season among all the marsh sites was winter 1998-1999 at Tubbs Island Marsh where average densities reached 17,140 $\pm$ 5,320 zooplankton per 0.25 m$^3$ (virtually all copepods; Fig. 9).

The remaining restored sites, Waterfront Marsh, Navy Marsh, and Pt. Edith Marsh had similar average seasonal densities (<250 zooplankton per 0.25 m$^3$) during all seasons and had zooplankton densities and taxa similar to the reference marshes rather than the three highest-yield marshes (Figs. 10, 11, 12). These three remaining restored sites are represented with the same scales (0-200 zooplankton per 0.25 m$^3$) as the two reference marshes.

Some of the marsh sites had statistically significant differences in zooplankton densities among years such as the restored Outer McNabney/Shell Marsh (Kruskal-Wallis: Chi$^2$ = 8.9, 2 df, p = .012). The years 1999 and 2000 yielded significantly greater zooplankton densities compared to the year 2001 at Outer McNabney/Shell Marsh (Mann-Whitney U = 165, corrected for ties, Z = -2.9, p = .003; U = 244, corrected for ties, Z = -2.2, p = .029).
There were significant differences among the years at Edith West Reference Marsh (Kruskal-Wallis: $\chi^2 = 15$, 3 df, $p = 0.002$). The year 1999 yielded significantly greater densities compared to 2001 (Mann-Whitney $U = 31$, corrected for ties, $Z = -3.2$, $p = .001$). There were significant differences in zooplankton densities among the years at Pt. Edith Marsh (Kruskal-Wallis, $\chi^2 = 15.9$, 2 df, $p < .001$). The year 1999 yielded significantly greater densities than 2001 (Mann-Whitney $U = 31$, corrected for ties, $Z = -3.2$, $p = .001$).

Statelands Reference Marsh had significant differences in zooplankton densities among the years of the study (Kruskal-Wallis: $\chi^2 = 31$, 9 df, $p < 0.001$). The year 1999 had significantly greater zooplankton densities when compared to 2000 and 2001 (Mann-Whitney $U = 74$, corrected for ties, $Z = -2.1$, $p = 0.037$; Mann-Whitney $U = 13$, corrected for ties, $Z = -2.3$, $p = 0.005$).

There were significant differences among the years at the Navy Marsh (Kruskal-Wallis, $\chi^2 = 16$, 2 df, $p < .001$). The years 1999 and 2000 yielded significantly greater zooplankton densities compared to 2001 at Navy Marsh (Mann-Whitney $U = 3$, corrected for ties, $Z = -2.5$, $p = 0.40$; $U = 18.5$, $Z = -3.7$, $p < .001$). Yearly densities at Waterfront Marsh were not compared due to too few seasons in 1999 (Fig. 5-12).

For each season at each marsh, cumulative seasonal means (including all taxons present in the samples) were calculated at all reference and restored marshes. For each seasonal zooplankton density in each year at all sites, the standard error of the mean was approximately equal to or less than the mean.
The Importance of Marsh Tidal Pools

The marshes Inner McNabney Shell, Outer McNabney/Shell, Tubbs Island, and Waterfront all have marsh tidal pools connected to the tidal channels. The reference marshes and remaining restored marshes have no such pools (Table 1). The marshes with marsh tidal pools connected to the tidal channels, except for Waterfront Marsh, all had significantly greater overall zooplankton densities compared to the reference marshes.

Overall, the presence of marsh tidal pools yielded a significant difference from marsh sites without tidal pools, with N = 8 (4 sites with pools, Kruskal-Wallis: Chi² = 87, 1 df, p < 0.001).

Densities of zooplankton and fish (fish density data based on several methods each, for reference and restored marshes, Kitting et al. 2001) each were grouped into five categories of (1) low abundance, with 50 or fewer zooplankton per 0.25 m³ or rare fish; (2) Medium low, with 100 or fewer zooplankton per 0.25 m³ or medium low fish abundance; (3) Medium, with 3,000 or fewer zooplankton per 0.25 m³ or medium fish abundance; (4) Variable high, with 5,000 or fewer zooplankton per 0.25 m³ or variable high abundance of fish; or (5) High, with >5,000 zooplankton per 0.25 m³ or highest abundance of fish. There were four sites with pools and four sites without pools, N = 8. There was a significantly positive correlation between zooplankton and fish densities, r² = 0.798, (80% correlation between zooplankton and fish densities, p < 0.05).

Taxonomic Diversity

The most abundant taxa at all marsh sites were identified from 1999-2000 by Kitting and Rees (Kitting et al 2001). Quantitative species data were not obtained for all sites.
throughout the years of the study. Overall, copepods were the most abundant taxon at all sites during the study, except at Pt. Edith Marsh and Waterfront Marsh where cladocerans were the most abundant taxon. The most abundant copepod species at both reference and restored marsh sites was the calanoid copepod *Eurytemora hirundoides* (Fig. 5-12 and Table 3).

Cladocerans were identified as *Daphnia magna* and were the second most abundant taxon overall at Inner McNabney/Shell Marsh and Outer McNabney/Shell Marsh, both marshes restored with tidal marsh pools. The third most abundant taxon at Inner McNabney/Shell Marsh was rotifers, listed in the “miscellaneous” taxa column. Overall the Tubbs Island Marsh (located in San Pablo Bay) had higher seasonal densities of water boatman, *Trichocoryxa reticulata* than cladocerans, and the reference marshes (Edith West and Statelands), yielded higher densities of cumaceans, *Cumella vulgaris* compared to cladocerans. The water boatman was the most abundant taxon at Inner McNabney/Shell marsh and Tubbs Island Marsh (Fig. 5-12 and Table 3).

Low densities of amphipod zooplankton, primarily *Gammarus limnaus*, appeared in all marshes but were most abundant at Inner McNabney Shell Marsh followed by Waterfront Marsh (both restored with marsh tidal pools), and Pt. Edith Marsh, restored without marsh tidal pools. Mysids, *Neomysis mercedis*, were rare or absent at all sites with an average seasonal high of only 130 per m³ in fall 1999 at rich Inner McNabney/Shell Marsh (Fig. 5-12 and Table 3).

Small fishes were rare at most sites in zooplankton tows but highest densities occurred at Inner McNabney/Shell Marsh. High densities of zooplankton grouped under
“miscellaneous” at Inner McNabney/Shell Marsh in winter 1998-1999 and spring 1999 were mostly rotifers (Fig. 5-12 and Table 3).

Overall, the Outer McNabney/Shell Marsh had the greatest diversity with approximately 10 different taxa in the “miscellaneous” category while Navy Marsh had only 2 taxa represented in this category (Fig. 8, 11). Most marshes were fairly similar in diversity of “miscellaneous” taxa (ranging from 2-10 miscellaneous taxa). All marshes except for Inner McNabney/Shell Marsh were also similar in overall average density of miscellaneous taxa (6-38 zooplankton per 0.25 m$^3$ in this category). However, due to the great densities of rotifers found at Inner McNabney/Shell Marsh in winter 1998-1999 and spring 1999, this site had greater densities of “miscellaneous” taxa overall (Fig. 7).

Additionally, no jellyfish (which can kill larval fishes and small crustacea) were detected in these marsh zooplankton samples (except a ctenophore rarely at Tubbs Island Marsh) despite analogous samples in deeper, open water during summer-fall (Rees and Kitting 2002).

DISCUSSION

The hypothesis that reference or historical marshes would yield greater densities of zooplankton was rejected for three out of four marshes with marsh tidal pools connected to the tidal creeks, Inner McNabney/Shell Marsh, Outer McNabney/Shell Marsh, and Tubbs Island Marsh. Waterfront Marsh (a restored marsh site with a marsh tidal pool) yielded significantly lower zooplankton densities when compared to one reference marsh, Statelands Reference Marsh.
Waterfront Marsh has a small marsh tidal pool located 1 km west of the entrance of the tidal channel, a pool too small and shallow for zooplankton net sampling, with only a few cm of water depth remaining at low tide. Thus, Waterfront Marsh Pool is flushed much more than the other (larger, deeper, micro-tidal) marsh tidal pools. The zooplankton samples taken at Waterfront Marsh were taken where open water first enters the marsh (consistent with sampling locations at all marshes); at this point, the marsh channel widens landward from approximately 1-m-wide to approximately 4-m-wide but the area is similar to a wider channel with steep banks approximately 2-m deep, rather than a micro-tidal pool as in the McNabney/Shell marshes.

However, Waterfront Marsh had increased seasonal densities of epibenthic invertebrates and small fishes during the study, consistent with increased epibenthic invertebrate and small fish densities at the three most abundant restored marshes with tidal pools (Inner McNabney/Shell, Tubbs Island, Outer McNabney/Shell) but inconsistent with other restored marshes lacking ponds (Navy and Pt. Edith) and Edith West Reference Marsh and Statelands Reference Marsh) (Kitting et al 2001). This discrepancy suggests that the particular features of Waterfront Marsh (increased flushing, including the small, singular shallow pool) influenced the low seasonal zooplankton densities recorded at this site (Fig. 5-12).

The effect of marsh tidal pools is most likely due to multiple factors including increased photosynthesis with subsequent phytoplankton and benthic algal growth in these deep (but shallower than tidal channels) larger areas of water. These pools also may serve as nutrient depositories of bird guano, further increasing algal growth. Also,
marsh pools connected to tidal channels may aid in retention of nutrients, phytoplankton, and zooplankton, preventing complete export during each outgoing tide.

Any differences in physical factors did not appear to determine the density of zooplankton among the marsh sites. The significant difference in salinity between the McNabney/Shell Marshes and the other marshes did not seem to have an overall impact on zooplankton as the McNabney/Shell marshes had the lowest average salinities and Tubbs Island Marsh had the highest average salinity but these three sites yielded the greatest overall zooplankton densities (Fig. 3).

Water clarity was significantly lower at Inner McNabney/Shell Marsh yet this marsh had the greatest zooplankton densities, and though it had significantly lower average Secchi depths (less water clarity) than Outer McNabney/Shell, there was no noticeable difference in Secchi depths between Inner McNabney/Shell Marsh and Tubbs Island Marsh (again the three most abundant marshes) (Fig. 3).

Due to high variability among most sites (seasonally and yearly), it is difficult to make any clear conclusions about overall temporal trends in zooplankton densities. However, it is likely that the great variability in zooplankton densities at the Tubbs Island Marsh was related to sudden shifts in salinity, as most aquatic animals are unable to withstand such sudden shifts in salinity (Fig. 9). Plans to address the silting at this site which caused the salinity shifts are being addressed by the managers of the refuge where this marsh is located.

A pattern of seasonal density may be evident at the McNabney/Shell marshes. The late summer and fall algal blooms (followed by fish kills, Kitting et al. 2001) these
marshes experienced could have influenced the relatively high then low zooplankton densities seen at both of these sites in summer and fall months (Fig. 7, 8).

Additionally, winter water quality might have been compromised due to excessive run-off in years of heavy rainfall, which could have caused a decrease in zooplankton abundance (Fig. 7, 8). During heavy winter rainfall periods, the leaking tidal gates at these marshes are fully open to outflow for various periods of time as a flood control measure. These flushing episodes, which generally occur every year, could have contributed to the low winter zooplankton densities through export of zooplankton. Winter 1998-1999 at Inner McNabney/Shell did not follow this pattern though sampling occurred after the rainy season had begun, January 23, 1999.

However, within the next 2 years, both McNabney/Shell marshes will be restored to increased, natural tidal amplitude for this area (approximately 0.5-1 m) and it is hypothesized that the reintroduction of normal tidal amplitude will produce comparable high densities of zooplankton during all seasons. Normal tidal amplitude should aid in circulation and aeration, and dilution of heavy run-off in the winter months during heavy rains, thus improving water quality for zooplankton and other organisms.

The presence of tidal pools has been proposed to be tested in the field in Southern Suisun Bay by locating several pools currently cut-off form tidal amplitude and re-sampling, at the entrance of the tidal channel, prior to and after introduction of tidal action. If marsh tidal pools are discovered to be the most significant factor influencing zooplankton abundance in restored sties, thought must be given to how the pools can be maintained since they may fill with silt, thus destroying the tidal pool, within a decade or
so (Resh et al. 1985). Additionally, new pools may form in a natural, expanding marsh (Kitting, 2001).

However Waterfront Marsh was created without much tidal amplitude initially in the early 1920s by dredging material from the current marsh channel for the adjacent road (Waterfront Road); and the small marsh tidal pool at the west end of the 1-km-long tidal channel is still present, although it is more shallow than marsh tidal pools at the other restored sites with tidal pools. Additionally, the Weir Marsh Tidal Pool (located within the restored Pt. Edith Marsh complex in summer 2001) had tidal action restored approximately 20-50 years ago and this pool existed (as a pool with muted tidal amplitude) prior to the construction of a dike by duck hunters, who cut off all tidal action to the pool approximately 75-100 years ago. It appears that pools with more muted tidal amplitude have low sedimentation rates, postponing silting in of the pool (Gill, unpublished).

Correlation of zooplankton abundance with fish abundance should continue to be tested elsewhere, as zooplankton is a major food resource for many juvenile fish species.

Though the participants in this ongoing exploration of marsh ecology are cautiously optimistic concerning restoration, they agree that restoration success is expected and achieved faster when restoration efforts are focused on areas designated as low-stress systems where normal marsh conditions existed and are likely to return with the introduction of tidal action. It is always wiser to conserve wetlands rather than to alter them and then attempt restoration (Zedler 2001).
However, results of this project were encouraging and because few marsh habitats are left to conserve in the San Francisco Bay Estuary, it is likely that restoration efforts can continue with improvements at future sites. These sites, though experiencing similar locations and climate, have variable factors (pools, tidal action, etc.) influencing animal abundance. These sometimes-unusual local factors must be taken into consideration in future marsh restoration attempts to avoid using a rigid, uniform model for every site (Zedler 2001). Yet overall, restoring marshes with marsh tidal pools may yield population densities of animals that are orders of magnitude greater than other sites.
Literature Cited


Fig. 1. San Francisco Estuary
Fig. 2. Marsh locations. 1: Statelands Reference. 2: Edith West Reference. 3: Tubbs Island Muted. 4: McNabney/Shell (Inner and Outer). 5: Pt. Edith. 6: Navy. 7: Waterfront. (Modified from Josselyn 1983)
TABLE 1: SUMMARIZED COMPARISONS OF NORTH SAN FRANCISCO ESTUARY MARSHES RESTORED TO VARIOUS DEGREES OF TIDAL AMPLITUDE OVER TIME (CONT.)

<table>
<thead>
<tr>
<th>RESTORED MARSH</th>
<th>TIDE</th>
<th>RANGE</th>
<th>POOLS</th>
<th>CONDITIONS</th>
<th>SITE ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFERENCE (NOT MODIFIED)</td>
<td>7 FT</td>
<td>2.1 M</td>
<td>NO</td>
<td>2M DEEP INTER-TIDAL CHANNEL</td>
<td>STATE LANDS</td>
</tr>
<tr>
<td>REFERENCE (NOT MODIFIED)</td>
<td>7 FT</td>
<td>2.1 M</td>
<td>NO</td>
<td>PERM 2M DEEP CHANNEL</td>
<td>EDITH WEST</td>
</tr>
<tr>
<td>RESTORED TO FULL TIDAL AMPLITUDE IN 1995</td>
<td>7 FT</td>
<td>2.1 M</td>
<td>NO</td>
<td>2M DEEP INTER-TIDAL CHANNEL</td>
<td>NAVY</td>
</tr>
<tr>
<td>RESTORED TO MICRO-TIDAL 1998</td>
<td>-0.1-0.4 FT</td>
<td>~0.30 M</td>
<td>YES</td>
<td>PERM POOLS AND CHANNELS</td>
<td>INNER McNABNEY SHELL</td>
</tr>
<tr>
<td>RESTORED TO MICRO-TIDAL 1998</td>
<td>0.2 FT</td>
<td>~0.25 M</td>
<td>YES</td>
<td>PERM POOLS AND CHANNELS</td>
<td>OUTER McNABNEY SHELL</td>
</tr>
<tr>
<td>RESTORED MUTED TIDAL AMPLITUDE 1999</td>
<td>4 FT</td>
<td>1.2 M</td>
<td>YES</td>
<td>PERM POOLS AND CHANNELS</td>
<td>TUBBS ISLAND</td>
</tr>
<tr>
<td>RESTORED MARSH</td>
<td>TIDE</td>
<td>RANGE</td>
<td>POOLS</td>
<td>CONDITIONS</td>
<td>SITE ID</td>
</tr>
<tr>
<td>----------------------</td>
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<td>-------</td>
<td>-----------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>RESTORED TO &lt;FULL TIDAL 1997</td>
<td>3 FT</td>
<td>1 M</td>
<td>YES</td>
<td>PERM. POOL AND CHANNELS</td>
<td>WATERFRONT</td>
</tr>
<tr>
<td>RESTORED TO FULL TIDAL 1995</td>
<td>6 FT</td>
<td>1.9 M</td>
<td>NO</td>
<td>2M DEEP INTER-TIDAL CHANNEL</td>
<td>PT. EDITH</td>
</tr>
<tr>
<td>Site</td>
<td>Mean</td>
<td>Std. Error</td>
<td>N</td>
<td></td>
<td></td>
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<td>-----------------------------</td>
<td>------</td>
<td>------------</td>
<td>----</td>
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</tr>
<tr>
<td>Edith West (reference)</td>
<td>26</td>
<td>5</td>
<td>47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statelands (reference)</td>
<td>77</td>
<td>18</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner McNabney (restored with pools)</td>
<td>8375</td>
<td>1021</td>
<td>63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer McNabney (restored marsh with pools)</td>
<td>2474</td>
<td>683</td>
<td>85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubbs Island (restored with pools)</td>
<td>4674</td>
<td>1266</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Navy (restored)</td>
<td>29</td>
<td>13</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt. Edith (restored)</td>
<td>52</td>
<td>13</td>
<td>54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterfront Road (restored with pools)</td>
<td>31</td>
<td>16</td>
<td>28</td>
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</tr>
</tbody>
</table>
Table 3 Taxa in Order of Abundance Compared Among Reference and Restored Marshes

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>Common Name</th>
<th>Native/Introduced</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference Marshes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Eurytemora hirundoides</td>
<td>calanoid copepod</td>
<td>Native</td>
</tr>
<tr>
<td>2. Cumella vulgaris</td>
<td>cumacean</td>
<td>Native</td>
</tr>
<tr>
<td>3. Daphnia magna</td>
<td>water flea</td>
<td>Native</td>
</tr>
<tr>
<td>4. Gammarus limnaus</td>
<td>gammarid amphipod</td>
<td></td>
</tr>
<tr>
<td>5. Neomysis mercedis</td>
<td>opposum shrimp</td>
<td></td>
</tr>
<tr>
<td><strong>Larval and juvenile fish</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Gasterosteus aculeatus</td>
<td>3-spine stickleback</td>
<td>Native</td>
</tr>
<tr>
<td>2. Leptocottus armatus</td>
<td>staghorn sculpin</td>
<td>Native</td>
</tr>
<tr>
<td><strong>Restored Marshes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Eurytemora hirundoides</td>
<td>calanoid copepod</td>
<td>Native</td>
</tr>
<tr>
<td>2. Daphnia magna</td>
<td>water flea</td>
<td>Native</td>
</tr>
<tr>
<td>3. Trichocoryxa reticulata</td>
<td>water boatman</td>
<td>Native</td>
</tr>
<tr>
<td>4. Gammarus limnaus</td>
<td>gammarid amphipod</td>
<td></td>
</tr>
<tr>
<td>5. Cumella vulgaris</td>
<td>cumacean</td>
<td>Native</td>
</tr>
<tr>
<td>6. Neomysis mercedis</td>
<td>opposum shrimp</td>
<td>Native</td>
</tr>
<tr>
<td>7. Large numbers of rotifers one season at Inner McNabney/Shell</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Larval and juvenile fish</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Gasterosteiis aculeatus</td>
<td>3-spine stickleback</td>
<td>Native</td>
</tr>
<tr>
<td>2. Dorsoma petenense</td>
<td>Threadfin Shad</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3. Overall average salinity (ppt), Secchi Depth/Water Clarity (cm), and Water Temperature (Celsius) at Reference and Restored Marshes 1999-2001. Error bars denote std. error.
Fig. 4. Logarithmic overall average densities of zooplankton at reference and restored sites from 1999-2001 (and fall season 2002 included in some site densities).
Fig. 5. Seasonal densities of zooplankton at Edith West Reference Marsh. Bars labeled (a) have significantly higher densities of zooplankton compared to the same seasons in different years (p < 0.05).

Fig. 6. Seasonal densities of zooplankton at Statelands Reference Marsh. Bars labeled (a) have significantly higher densities of zooplankton compared to the same seasons in different years (p < 0.05).
Fig. 7. Seasonal densities of zooplankton at Inner McNabney/Shell Marsh (restored).

Fig. 8. Seasonal densities of zooplankton at Outer McNabney/Shell Marsh (restored). Bars labeled (a) have significantly higher densities of zooplankton compared to the same seasons in different years (p < 0.05).
Fig. 9. Seasonal densities of zooplankton at Tubbs Island Marsh (restored marsh in San Pablo Bay). Bars labeled (a) have significantly higher densities of zooplankton compared to the same seasons in different years (p < 0.05).
Fig. 10. Seasonal densities of zooplankton at Waterfront Marsh (restored).

Fig. 11. Seasonal densities of zooplankton at Navy Marsh (restored). Bars labeled (a) have significantly higher densities of zooplankton compared to the same seasons in different years ($p < 0.05$).
Fig. 12. Seasonal densities of zooplankton at Pt. Edith Marsh (restored). Bars labeled (a) have significantly higher densities of zooplankton compared to the same seasons in different years (p < 0.05).
Chapter 2

COMPARING NEWLY DISCOVERED HYDROBIID SNAIL DENSITIES AND RECRUITMENT AMONG REFERENCE AND RESTORED MARSHES IN SOUTHERN SUISUN BAY, SAN FRANCISCO ESTUARY

ABSTRACT

For over three years, aquatic animals were monitored approximately monthly in seven restored and historical brackish marshes around southern Suisun Bay of the San Francisco Estuary. Non-destructive seasonal sampling included approximately four replicate refugia traps (modified mesh minnow traps), each representing a total area of 1 m² located at the entrance of the tidal channel in all marshes. Common aquatic invertebrates, including amphipods, isopods, and gastropods, were abundant in several restored marshes compared with reference marshes. Only sites with marsh tidal pools yielded numerous aquatic animals. Several sites with marsh tidal pools also yielded unusual, thriving hydrobiid snails (a close relative of Tryonia imitator-California’s endangered “brackish water snail.”) These hydrobiid snails ranged in shell length from < 0.50 to 5 mm. A national authority has not been able to identify the snails but they appear to be Hydrobia andersoni, previously known only from fossils on this ancient San Joaquin River. Sediment cores at the older restoration site with the most muted tidal action yielded these snails at least 130 cm deep in the ancient peat soil. Slow sedimentation rates and unusually low mercury levels in the peat soil in these isolated marshes suggest a probable age of approximately 200 years or more for shells at this
depth, indicating these snails are natives. Subsequent mini-quadrat sampling at the oldest (>20y) restoration site yielded high densities of snails, an average of approximately 200-300 snails per 25 cm² in the upper several centimeters of mud and approximately 60-80 on vegetation (primarily Entermorpha green algae). Juvenile snails (represented as snails with shell lengths of < 0.50 mm) occurred in all seasons on both substrates at the largest tidal pool. Average seasonal densities were significantly greater at this old restoration site with a large pool when compared to the more recently restored tidal site. Quantitative sampling of other aquatic invertebrates at the old restoration site yielded high average densities of a variety of common aquatic invertebrates, primarily ostracods. As these hydrobiid snails demonstrated seasonal recruitment and high average densities on both substrates for over a year, and were abundant with other aquatic invertebrates, marsh tidal pools seem to be an important feature in restoring common and possibly ancient assemblages of aquatic invertebrates.

INTRODUCTION

In the past 200 years, approximately one third to one half of the wetlands of the coterminous United States have been lost due to human impact (Havens et al. 1995). Included are tidal wetlands, which are important habitats at some point in the life history of 75% of the commercially harvested fish and invertebrates in the United States (Chambers 1992). Approximately 95% of the tidal wetlands of California have been diked, dredged, or filled (Josselyn 1984) (Fig. 1 a).
Such major loss of wetland habitats in San Francisco Estuary has led state, local, and federal agencies and university researchers to unite in the CALFED Bay Delta Program, which already has restored several marshes in the Estuary to some degree of tidal action.

Wetland ecosystem restoration is the process of reestablishing the physical, chemical, and biological conditions at degraded wetland sites that still possess some of the features (such as elevation and topography) of the original wetlands. The most effective restoration is accomplished by removing or altering the features that prevent the degraded land from functioning at full value (Weinstein et al. 2001).

The brackish marshes in this project are located in Southern Suisun Bay, where tidal action was restored by dismantling tidal gates (which cut off tidal action) or by cutting through levees, allowing tidal channels from the Delta or an historic slough to restore tidal amplitude to marshes previously cut off from tidal action or, in one case, by the natural erosion of an unattended dike.

Given that assemblages of animals investigated have differed along with the sampling methods, many studies demonstrate that natural marshes have greater densities and species diversity compared to marshes restored to some degree of tidal action, particularly in the initial years following restoration (Scatolini and Zedler 1996).

To assess animal colonization in several restoration efforts, comparative marsh monitoring took place for approximately 3 years after restoration of tidal action to determine densities of zooplankton, epibenthic macroinvertebrates, and fishes, among various restored and reference marshes. Physical factors of both reference and restored
marshes were also monitored through measurements of salinity, secchi depths (water clarity), and water temperature.

The hypothesis is that restored marshes will yield lower population densities both in introduced and native and/or ancient taxa when compared to remaining historical marshes (>100 years old). An alternative hypothesis is that particular features of restored marshes will yield higher abundance of both introduced and native taxa, and possibly recruit and restore certain ancient populations of animals.

Focusing on invertebrate populations in assessing marsh restoration is important (Peck et al. 1994). They contribute to litter decomposition, thus food web support, and an understanding of their distribution and abundance is essential to assess the functioning of restored systems (Scatolini and Zedler 1996). Population densities of marsh organisms (among vegetation and soft mud) are difficult to assess accurately, so a combination of multiple sampling methods is recommended, particularly for marsh fishes (Rulifson 1991).

Study of a few indicator species is suggested when evaluating the health of a restoration project (Peck et al. 1994). In this study, the hypothesis that reference marshes will yield higher densities of invertebrates is tested by comparing the density of a newly discovered, apparently native, ancient hydrobiid snail among restored and reference marshes in Southern Suisun Bay (Fig. 1 b).

In the western United States, most hydrobiid snails are found in saline springs in landlocked states such as Arizona, Nevada, and New Mexico (Hershler et al. 1999). The only hydrobiid previously identified from the tidal wetland habitats of the coast of California
is the endangered brackish water snail *Tryonia imitator* (Kellogg 1980; Hershler *et al.* 1998). Of the ten known historical populations of this endangered snail, *T. imitator* is found only in three localities within the area of San Luis Obispo County to Sonoma County (Kellogg 1980).

**METHODS**

**The Sites**

The seven tidal marshes compared systematically, two reference and five restored, all are located within San Francisco Estuary in Southern Suisun Bay, located at 38 degrees 2.5’ N, 122 degrees 4.4’ W (Fig. 1 a). The reference or historical marshes included Statelands (wide and small channels) and Point Edith West (deep and shallow channels). Neither marsh has connected marsh tidal pools and both have 1-m or 2-m-deep channels at low tide with approximately full tidal action of 2 m (Table 1).

The restored marshes included Point Edith, restored to full tidal action in 1995 with no associated marsh tidal pools. However, the Weir Marsh Tidal Pool (approximate area of 1000 m²) was identified within the Point Edith complex of marshes as an older (>20 years post-restoration) site restored to muted tidal action (approximately 0.5 m tidal amplitude) by the natural erosion of an unattended dike apparently constructed by duck hunters. Navy Marsh (within the jurisdiction of the United States Department of Defense) was also restored in 1995 to full tidal action with no connected marsh tidal pools. A small, non-tidal pool located within the Navy complex (approximate area of 5 m²) in an unrestored area also monitored as a non-tidal pool for comparison. Waterfront
Marsh has muted tidal amplitude with a small, inundated marsh tidal pool (at the western end of a 1-km-long tidal marsh channel) which is approximately 200 m² and the site was restored to approximately 1-m tidal action in 1997 (Fig. 1 c).

The other two restored sites included Upper/Inner McNabney Shell Marsh and Lower/Outer McNabney Shell Marsh (1-km-south, up Peyton Slough from Suisun Bay). These two marshes received the least tidal action in the form of leaking tidal gates (approximately 0.25 m tidal amplitude) and received low-salinity, secondary reclaimed water from a nearby water treatment plant. Both McNabney Shell Marshes consist of permanent marsh ponds with approximately 1-m-deep channels, restored to muted tidal action in 1998 (Table 1). Reference and restored marshes in the study are brackish marshes (salinities varying from 2-20 ppt relative to seawater at approximately 32 ppt).

**Physical Factors**

Salinity, conductivity, and water temperature were monitored approximately monthly using YSI conductivity meter and sondes (data loggers). Secchi depth was noted with a secchi disc, which yields water clarity.

**Sediment Cores**

To ascertain if the snails are introduced species, several sediment cores were taken at the older restoration site, Weir Tidal Marsh Pool, during three separate months. Sediment core diameters varied due to the difficulty of pushing the cores into the substrate. Smaller diameter cores were needed in some areas of the marsh. The cores were not taken at random quadrat areas but were taken in open mud about 1 meter from
dense marsh vegetation, where it was possible to successfully perform this type of sampling.

**Refugia Mesh Live Animal Traps**

Macroinvertebrate and fish sampling occurred approximately monthly (not all sites were accessible each month) with benthic net sweeps for macroinvertebrates and flexible mesh minnow-traps for separate nekton sampling (swimming invertebrates and fishes). The mesh refugia traps had an approximately 4 cm funnel at both ends with 0.5 m² areas inside and out, totaling approximately 1 m² (imported by Nichols Net, Illinois). Mesh openings were approximately 2 mm wide. Because the hydrobiid snails also colonized such shaded habitats, two to four traps were employed at the tidal channel entrance near emergent vegetation, >2 m apart. Spacing was neither uniform nor random, due to access, tidal currents and murky water.

The hydrobiid snails appeared in the refugia mesh animal traps. When the traps were recovered from the water, counts were taken of live invertebrates of body length of >1 mm long from outside and inside the traps. Counts were taken visually and through touch (running a hand over all areas of the trap, inside and out). Dead, eroded shells were not counted in this sampling (except in cores above). Identification to species level (except for the newly discovered hydrobiid snails) was usually impossible in the field, but unidentified species were taken back to the laboratory at California State University at Hayward live for identification. Data were entered on a Microsoft Excel database.
Sediment Traps

Sediment traps (cups 10 cm tall) representing an approximate area of 1/20 m², were anchored on the bottom sediment at all sites near the entrance of the tidal channel. Two cups were generally employed and were connected to a piece of PVC pushed into the mud to secure the traps and allow them to be recovered. These sediment traps were counted approximately monthly (as not all sites were accessible each month). Sedimentation levels in the cups were noted and the animals in the sediment cups were sieved through a 1-mm-mesh. All sediment cup snails were counted and entered on the database at CSUH.

Mini-Quadrat Animal Sampling

The Weir Marsh Tidal Pool had such high visible densities of hydrobiid snails that circular mini-quadrats (area of 25 cm²) were used as a more quantitative sampling method in addition to the refugia mesh animal traps and sediment traps. These circular quadrats were 120 ml sample cups with the cup mouth representing the area of the sample, 25 cm². Quadrat samples were taken randomly (with the use of a random number table) on a 40-m-long transect along the shore at Weir Marsh Tidal Pool, a 10-m-long transect at Waterfront Marsh Tidal Pool, and a 2-m-long transect at the non-tidal Navy Pool. Four quadrat samples were taken seasonally on mud and algae, primarily Enteromorpha algae. Samples were taken for five seasons (spring 2002-spring 2003) at the Weir Marsh Tidal Pool, four seasons at the Waterfront Marsh Tidal Pool site (summer 2002-2003) and two seasons at the non-tidal Navy Pool.
The sampling cup opening was placed on the mud or on vegetation and pushed into the substrate approximately 1-cm-deep. The lid to the sampling vial was moved under the cup, across the opening to trap specimens within this area. At Weir Marsh Tidal Pool and Waterfront Marsh Tidal Pool, transects were located along the shore of the pool beginning where the tidal creeks connected to the pools. An additional four, 25 cm² quadrats were taken on mud 3-5 m out in the pool along the same 40-m-long transect at Weir Marsh Tidal Pool in summer 2002 and similar quadrats were obtained at the Waterfront Marsh Tidal Pool along the same 10-m-long transect in spring 2003, during an exceptionally low tide, which made sampling out in the pool feasible at this site.

Snails were transported live from the field to CSUH and the Shore Lab, sorted and counted by shell size class (shell length: <0.50 mm; 0.50-1.5 mm; 1.5-2.5 mm; 2.5-3.5 mm; 3.5-4.5 mm; 4.5 mm and over). Due to the size of juvenile hydrobiid snails (<0.50-mm), samples were not sieved and all samples were counted under a microscope (using 7-30 X magnifications).

In fall 2001, five aquaria were established at CSUH, each with ten snails (3.5-4.5 mm in shell length) from the Weir Marsh Tidal Pool. Snails were washed with distilled water before being put into a tank of water obtained from the marsh to remove any veliger larvae, which might have been present. The aquaria were observed for any snail egg masses weekly, and feeding behavior also was observed.
Data Analysis

Since not all marshes were accessible each month, data from the refugia traps and sediment traps were grouped as seasonal blocks each year: spring months were designated as March, April and May; summer months were June, July and August; fall months were September, October and November; and winter months were December, January and February. The 25 cm² quadrats were taken only seasonally.

All data were tested for normality and homogeneity of variance using the Kolmogorov-Smirnov and Levene’s test. Both physical and biological factors did not comply with the assumption of homogeneity of variance, so non-parametric tests were used for analysis. The Kruskal-Wallis test was used to test for differences in hydrobiid snail densities among sites and between seasons (specifically at the Weir Tidal Pool) using SPSS (a statistical software program).

RESULTS

Presence/Absence of Newly Discovered Snails

After approximately three years of sampling using a variety of techniques at both restored and reference marshes, no hydrobiid snails and very few other aquatic animals were found at either reference marsh or at any of the five restored marshes lacking marsh tidal pools connected to the tidal creeks.

Snails colonized mesh minnow refugia traps, representing an approximate area of 1 m², at two marsh sites with marsh pools restored to tidal action, located at Weir Marsh Tidal Pool (the older restoration site, with a more muted tidal amplitude) and Waterfront
Marsh (the more recent restoration site, with a greater tidal amplitude). Refugia traps were placed at the entrance of the tidal channel to the marsh (similar to trap placements at all marshes). At this site, the small marsh tidal pool was located at the west end of a 1-km-long tidal channel (hence the entire marsh is referred to as Waterfront Marsh, while the pool area is referred to as Waterfront Marsh Tidal Pool). Additionally, hydrobiid snails also colonized the mesh refugia trap in a non-tidal, small isolated pool named Navy Pool (an unrestored, higher marsh area within the restored Navy Marsh complex) (Fig. 1c).

At the two tidal sites where hydrobiid snails were present (Weir Marsh Tidal Pool and Waterfront Marsh), the mesh animal traps also yielded higher population densities of other common aquatic invertebrates such as amphipods and isopods, and generally a greater diversity of species, both native and introduced, compared with the two reference sites and the other restored sites lacking marsh tidal pools connected to the tidal channel (Evans and Kitting 2001). Additionally the majority of restored tidal marshes with marsh pools connected to the tidal creeks yielded higher densities of zooplankton compared to the reference sites and restored marshes lacking marsh tidal pools (Davis 2004, Ch. 1).

**Sediment Cores**

Dead, eroded snail shells matching those of live specimens were found in the sediment deeper than 90 cm in three out of six deep core samples. One core yielded six shells in the depth range of 91-110 cm and a second core yielded a shell in the depth range of 131-140 cm. The deepest sediment core sample yielded four shells 161-170 cm deep in the
ancient peat soil, apparently pre-dating major sedimentation during the California gold rush and expanded human activity, indicating that these snails appear to be native.

After the California gold rush, mercury content of sediments reportedly rose, and mercury analyses of these deep sediments by Dr. Joy Andrews at California State University, Hayward showed unusually low mercury concentrations (Andrews, pers. comm.), further dating those strata as pre-European disturbance, before the gold rush and mercury deposition of approximately 150 years ago (Malmund-Roam, Contra Costa County Mosquito Abatement, pers. comm.). Dead snail shells also appeared isolated in various strata above 91cm depth, suggesting that these snails or habitats may have been patchy. Only the upper <1 cm of sediment yielded these live or freshly dead (uneroded) snail shells, where they were present at an average of approximately 200-300 shells per 25 cm²

Though a national authority did not identify the hydorbiid snails, James McLean, agreed with the present author that at least one species is likely a morph of Hydrobia andersoni, previously known only from fossil shells found inland, from up the ancient San Joaquin River (Kitting and Davis 2002).

Physical Factors

There were no significant differences in overall salinity, secchi depth (water clarity), and water temperature between the restored marshes of Pt. Edith (where Weir Tidal Marsh Pool is located) and Waterfront Marsh—the two tidal sites where the snail was discovered (Fig. 2, with overall average and std. error). Even though it is non-tidal, the Navy Pool did not demonstrate significant differences in physical factors when compared
to the above mentioned tidal marshes where the snail was discovered. Due to the non-tidal nature of the Navy Pool, physical factor comparisons with tidal sites are not included in Fig. 2, but physical factors for the restored Navy Marsh (where the pool is located in a currently unrestored area) are included (Fig. 2).

Seasonal and Spatial Densities Compared Among the Colonized Marshes

Though the mesh animal traps, representing an approximate area of 1 m², were placed at the entrance to the tidal channel near emergent vegetation at all reference and restored marshes in the study, snails only colonized the animal traps at three marsh pools (Weir Marsh Tidal Pool, Waterfront Marsh Tidal Pool, and Navy Pool-a non-tidal pool). Average snail densities for only three seasons were compared using this sampling method due to the intermittent theft of traps at all sites and the discovery of the Weir Marsh Tidal Pool late in the study, summer 2001.

Weir Marsh Tidal Pool (the oldest restoration site with the more muted tidal action), yielded the greatest overall snail densities on the mesh refugia traps, particularly during summer of 2001 with over 80 snails per m². Average snail density per m² at the Weir Marsh Tidal Pool dropped in October 2001, but increased to a similar average density in spring 2002 (Fig. 3, with mean and std. error).

At the Waterfront Marsh (where the tidal channel enters the marsh), no snails were detected for summer 2001, however, they reappeared on the traps in fall 2001 at an average of approximately 5 snails per m² mesh and increased to approximately 10 snails per m² by spring 2002 (Fig. 3). The population at the Navy Pool reached an average of over 20 snails per m² mesh in both summer and fall 2001 but dropped to under 20 per m².
in spring 2002 (Fig. 3). Overall snail densities at the two tidal sites (Weir Marsh Tidal Pool and Waterfront Marsh) were compared and the Weir Marsh Tidal Pool had significantly higher densities of snails than did Waterfront Marsh (Kruskal-Wallis, Chi² = 5.5, 1 df, p = 0.020). Seasonal comparisons were not made due to the small number of seasons for which data were available.

In addition to the mesh animal traps, sediment traps (cups) representing an approximate area of 1/20 m² were placed at all reference and restored marshes and again the hydrobiid snails were found in only the two tidal sites where the snails had colonized the refugia mesh traps (Weir Marsh Tidal Pool and Waterfront Marsh). Sediment cups were not censused routinely at the Navy Pool, a non-tidal area with low sedimentation rates. These sediment cup censuses were available for 7 seasons, as this sampling device was undisturbed throughout the course of the study.

The average seasonal snail densities at Weir Marsh Tidal Pool were <30 snails per 1/20 m² cup in each of the first four seasons (fall 2001, winter 2002, spring 2002, and summer 2002). However, in the following three seasons (fall 2002, winter 2003, and spring 2003), the average seasonal density of snails per 1/20 m² reached over 100 animals per season. Average seasonal densities of snails per 1/20 m² at the Waterfront Marsh were <10 snails per season (Fig. 4, with mean and std. error).

There were no significant differences between seasonal densities at either tidal site. Overall snail densities per 1/20 m² were compared between Weir Tidal Marsh Pool and Waterfront Marsh and Weir had significantly greater snail densities than Waterfront (Kruskal-Wallis, Chi², and 1 df, p <0.001)
The two sampling techniques (mesh refugia traps and sediment cups) demonstrated the persistence of the hydrobiid snails at the three pool sites, with greater abundance of snails found at the Weir Marsh Tidal Pool. However, since those methods did not reflect the high visible densities of snails observed along the shore at the Weir Marsh Tidal Pool site, the 25 cm² quadrats were employed as a more quantitative sampling method.

Samples were obtained on mud and vegetation (primarily Enteromorpha algae) to determine average seasonal snail densities on both substrata. The average snail density per 25 cm² on mud was greatest in the summer 2002 season while the average snail density on vegetation was greatest during the winter 2003 season. However, average snail densities on both substrata showed variability throughout most seasons (Fig. 5, with mean and std. error).

Using a Kruskal-Wallis test, no significant or nearly significant differences were detected among seasons or between substrates at Weir Marsh Tidal Pool (p > 0.245, as above). Snail densities on mud were compared to similar quadrat data from the other tidal site, Waterfront Marsh Tidal Pool (samples taken in the small pool at the end of the 1-km-long tidal channel) after summer 2002. Snail densities in 25 cm² at the Waterfront Marsh Tidal Pool averaged <10 snails per 25 cm² in summer 2002 and approximately 20 snails per 25 cm² in spring 2003. The non-tidal Navy Pool was similarly sampled only twice in spring 2002 and spring 2003 as only one snail was found there using this type of quadrat sampling (Fig 6, with mean and std. error).

The overall density of snails in 25 cm² was significantly greater at Weir Marsh Tidal Pool vs. Waterfront Marsh Tidal Pool (Kruskal-Wallis, Chi², 1 df, p < 0.001). Though
average spring 2003 snail densities per 25 cm\(^2\) appeared fairly similar between Weir Marsh Tidal Pool and Waterfront Marsh Tidal Pool, actual snail densities along the shore at the Weir Marsh Tidal Pool were likely much higher in patches then.

Due to an unseasonably hot day in early May 2003 (ambient temperatures in the shade of over 35 degrees C), the author observed hydrobiid snails congregating in dense, large patches of shade or in available small pools of water—even in groups forming vertical rows in the shade cast by Tule stands. As transect sampling was conducted using a random number table, none of the areas with visibly high densities were sampled during the spring 2003 sampling at Weir Marsh Tidal Pool. In one such area of high density, the author put the aperture of a sample cup over a congregation of snails and made an indentation in the soft mud. The area of the cup opening was completely filled with snails indicating an approximate number of 360 snails per 25 cm\(^2\).

In summer 2002, similar 25 cm\(^2\) quadrats were taken 3-5 meters out from the shore in Weir Marsh Tidal Pool to compare the density of snails away from the shore to the customary mini-quadrats taken along the shore, near emergent vegetation. The average seasonal density on mud (vegetation was patchy and difficult to reach away from the shoreline) was surprisingly similar with approximately 250 snails per 25 cm\(^2\) out in the tidal pool 3-5 m, and approximately 280 snails per 25 cm\(^2\) along the shore (Fig. 7, with mean and std. error).

Similar quadrats were taken during the spring 2003 season at Waterfront Marsh Tidal Pool (when the average number of snails per 25 cm\(^2\) was greatest), and at this site average snail densities in 25 cm\(^2\) also were similar with slightly higher densities of snails.
out in the pond compared to along the shoreline near emergent vegetation, with an average of approximately 50 snails / 25 cm$^2$ when 3-5 meters out in the tidal pool and approximately 20 along the shore (Fig 7).

During an unusually high tide during winter sampling at Weir Marsh Tidal Pool (approximately +6.5 feet relative to mean lower low water), four, 25 cm$^2$ quadrats were taken 3-5 meters away from the shore edge (towards the higher marsh, in vegetation), primarily Distichlis salt grass and some Ruppia widgeon grass. No hydrobiid snails were found in these samples at that time.

**Seasonal and Spatial Recruitment of Juvenile Hydrobiid Snails**

Juvenile recruitment data (as appearance of juveniles) were obtained seasonally for over a year at the Weir Marsh Tidal Pool, the old restoration site where snail densities were greatest. Average seasonal densities of snails were obtained on both mud and vegetation (primarily Enteromorpha algae). Though juvenile recruitment occurred each season on both substrates at the Weir Marsh Tidal Pool, the average seasonal density of juvenile snails (<0.5 mm in shell length) was greatest in summer 2002, when the average density of juvenile snails was approximately 60 per 25 cm$^2$ on algae and approximately 30 on mud (Fig. 8, with mean and std. error). However, these approximately 50% differences were neither statistically significant between these substrata or among seasons (Kruskal-Wallis, p = .945, p = .158 respectively), comparing the very patchy recruitment of juvenile hydrobiid snails at this site (with coefficients of variation, Std. Dev. / Mean, approximately 5).
Due to low average snail densities (<5 snails per 25 cm²) persisting at the Waterfront Marsh Tidal Pool in summer 2002, fall 2002, and winter 2003, data on recruitment of juveniles were obtained for one season, spring 2003, with an average of only 3 juveniles per 25 cm² quadrat on mud-algae were too patchy there. Overall average juvenile recruitment of snails per 25 cm² was compared between Weir Marsh Tidal Pool and Waterfront Marsh Tidal Pool and the Weir site had significantly greater juvenile recruitment (Kruskal-Wallis, Chi² = 11, 1 df, p = 0.001).

Shell Length Size Classes

From the shell length data taken at Weir Marsh Tidal Pool, no pattern of seasonal recruitment or growth was clear either on mud or algae. However average seasonal size classes appeared to be more uniform on algae than on mud. Average seasonal densities of (small) snails with shell lengths of 0.5-1.5 mm were low during all seasons on mud and the largest, most mature snails (4.5-5.0 mm in shell length) appeared in low densities for all seasons on both substrates (Fig 9, 10, each with mean and std. error). Seasonal differences were neither significant nor nearly so, with regard to shell length classes on algae (Kruskal-Wallis, Chi² = 10, 2 df, p = 0.40), but differences were significant on mud. The season spring 2003 had significantly lower snail densities of all size classes compared with the other seasons, (Mann-Whitney U minimum of 156, maximum p = 0.040).

Qualitative data on snail mortality in the 25 cm² quadrat samples suggested more dead, empty snail shells (not recently deceased) in the 3.5-4.5 mm shell length range in
the winter season on both mud and algae when compared to other seasons and other size
classes. However, many live snails persisted during winter, as plotted.

**Other Aquatic Invertebrates**

Quantitative data were taken on other aquatic invertebrates found in the 25 cm²
quadrats at the Weir Marsh Tidal Pool for over a year. The next most abundant
invertebrate found in these samples besides the hydrobiid snails, were ostracods followed
by oligochaetes on both mud and algae (Fig. 11, 12). Other aquatic invertebrates present
in the samples were midge larvae, aquatic insect larvae, amphipods, and copepods.

**Laboratory Observations of Feeding and Reproduction**

In the laboratory the hydrobiid snails were observed feeding on filamentous algae,
including cyanobacteria and chains of small diatoms. Groups of approximately 5-6 snails
were often observed feeding on the surface of the water, using the water tension to
suspend them while feeding. In these groups, snails were also observed feeding on algal
growths on each other’s shells. The snails were also observed feeding off of the bottom
and on the sides of the aquaria. In the field, snails were observed (at low tide) feeding on
mud and algae in the pools.

In one aquarium, 10 individuals (unsexed) produced over 200 young by October 2001.
(They had been placed in the aquaria in July 2001.) These snails appeared to brood their
young, as weekly observations for egg masses for over two months revealed no egg
masses or veligers, and no snail egg masses or veliger larvae were noted in any
zooplankton samples at either Weir or Waterfront.
The hydrobiid snails appear to be sexually dimorphic with females being larger. Large snails (4.5-5.0 mm) selected for dissection often yielded juveniles less than 250 micrometers in shell length in the mantle cavity while smaller dissected snails (<3.5 mm) did not yield brooded juveniles. Brooded snails appeared to leave the female at approximately 0.25 mm shell length, and <0.50 mm juveniles were common at Weir Tidal Marsh Pool.

Inadvertently, one aquarium (salinity normally was regulated between 7-11 ppt.) reached 42 ppt. and surprisingly, none of the snails in this aquarium perished.

DISCUSSION

Though the discovery of these hydrobiids was an unexpected result of the CALFED restoration and subsequent ecological monitoring program, the lack of these hydrobiids in the reference or historical marshes which have not been altered (diked, dredged, or filled) was also unexpected and surprising. The abundance of these snails along with significantly higher densities of common invertebrates rejects the hypothesis that reference or historical marshes will have more abundance and diversity of species and adds to the growing evidence of the importance of marsh tidal pools in recruiting high densities of epibenthic invertebrates, zooplankton and fishes (Evans and Kitting 2001, Davis Ch. 1).

Evidence of snail shells found in the ancient peat at the Weir Marsh Tidal Pool, accompanied by low mercury levels at this depth of sediment suggests that the snails are most likely Hydrobia andersoni, a living fossil. Additionally, this species has been noted
to exhibit variable shell morphology (Moore et al. 1952), which spans all morphs found in these marshes.

Like *Tryonia imitator* (the only endangered brackish water snail on the west coast of the United States) and some other hydrobiid snails, the snails from these marshes appear to brood their young and while several hydrobiids incorporate multiple modes of reproduction, the lack of egg masses and veligers noted throughout the field study and the lack of any observed egg masses and veligers in the lab, suggests that these snails rely on brooding young as their primary, perhaps exclusive, reproductive mode.

Many hydrobiid species demonstrate recruitment of juveniles throughout the year and the hydrobiids at the Weir Marsh Tidal Pool exhibited this type of recruitment pattern, though it seems likely from the 25 cm² quadrats at the Weir Marsh Tidal Pool that summer months are the most prolific season for juveniles (Fig. 8). Though significantly higher densities of juvenile (<0.50 mm in shell length) and young snails (0.50-1.5 mm in shell length) did not occur on algae compared to mud, generally average densities of juveniles were greater on algae than on mud. That tendency may suggest that the juvenile and smaller snails are more sensitive to anaerobic or dryer mud conditions, which might occur away from vegetation during low tides in the summer months.

The marsh tidal pools (Weir and Waterfront) containing the snails were inundated frequently; even the Navy Pool did not dry up during the study. However, the hydrobiid’s ability to withstand salinities greater than seawater (approximately 42 ppt.) with no mortality in the laboratory, suggests that they may have evolved to also withstand environments subject to hypersalinity, such as small scattered pools occurring higher in
the tidal marsh, which might receive extremely muted, or sporadic tidal action (though no hydrobiids were found during one season of sampling 3-5 m away from the shoreline in the higher marsh at Weir Tidal Marsh Pool).

The abundance of snails at Weir Marsh Tidal Pool and the presence of the snails in the non-tidal, higher marsh Navy Pool add to the evidence of the importance of marsh pools in this animal’s recruitment. Attempts should be made to identify and sample such scattered, isolated marsh pool areas as duplicates to the Navy Pool site, a non-tidal pool area in a marsh isolated from tidal action.

It appears highly unlikely that these hydrobiid snails, found deep in cored peat, are an introduced species as most western species of hydrobiids are found in saline, warm water springs in the western states and the brackish water hydrobiids of tropical climates would not be expected to survive the winter months in Southern Suisun Bay, when temperatures routinely drop below freezing. Weir Marsh Tidal Pool and Navy Pool have even been observed frozen with ice during one winter observation (Kitting, pers. comm.). Furthermore, the recently invading, tiny, New Zealand (hydrobiid) mud snail is distinctive, and found typically in freshwater streams.

Not only do the snails in the present study, apparently *Hydrobia andersoni*, persist during the winter months (though mortality of the larger snails, approximately 4 mm in shell length, is greater in the winter months) but recruitment of juveniles also appears during this season.

Though functional replacement (colonization by all animals) at the Weir Marsh Tidal Pool would have been expected to already occur, as the restoration is more than 20 years
old, even the young Waterfront Marsh had more abundant and diverse aquatic invertebrates than the reference marshes did. Additionally, though the Weir Marsh Tidal Pool is an older site, the expectation would be that the reference marshes would at least be equal in abundance and diversity of aquatic invertebrates as our various restoration sites. Yet the reference marshes had few aquatic animals (Evans and Kitting 2001, Davis, Ch 1).

The 25 m² quadrat samples at Weir Marsh Tidal Pool not only yielded consistently high snail densities, but consistently high seasonal densities of other invertebrates such as ostracods. The consistent abundance of aquatic animal life in such small areas at this site suggests that the Weir Marsh Tidal Pool’s natural restoration of tidal action was effective. The Waterfront Marsh Tidal Pool too, though not as high in snail densities as Weir Marsh Tidal Pool, has consistently yielded high densities of other common invertebrates.

However, duplicates of older and younger restoration marshes with muted tidal action would be needed in a study to make any clear conclusions concerning the effect of age on aquatic animal density and diversity. It has been proposed to test the importance of marsh tidal pools in the field using several non-tidal marsh pools within the restored Pt. Edith complex. Sampling would occur at the tidal channel before and after the introduction of tidal action.

The restored brackish marshes in the CALFED project represent marshes that are relatively low stress systems that have not been significantly altered and such systems respond well to restoration efforts compared to wetland creation efforts (Zedler 2001). The newly observed importance of marsh tidal pools should influence future restoration
efforts. If restoration to tidal action is attempted at similar sites then the restoration effort might maximize its success through restoration of areas where inundated marsh pools previously existed. As an alternative, creation of a marsh tidal pool in a previous marsh (such as at the Waterfront Marsh Tidal Pool) would be an option.

Dredging of the Waterfront Marsh Tidal Pool and 1-km-long channel occurred in approximately 1924 to supply material for the adjacent Waterfront Road, which created the present tidal pool and channel after tidal action was restored more recently. Both the Weir Marsh Tidal Pool and the Waterfront Marsh Tidal Pool area still exist today, suggesting that such features as marsh tidal pools do persist for some time and are not quickly filled with sediment, especially in marshes with muted tidal amplitude (Gill, unpublished). Other tidal pools are predicted to fill with sediment (Resh et al. 1990).

Even given the success of some of these CALFED restoration efforts and the possibility of successful future efforts in such systems, the priority should always be conservation of existing natural wetlands rather than restoration or creation (Zedler 2001).

LITERATURE CITED


Fig. 1b. Hydrobiid Snail
Fig. 1c. Southern Suisun Bay Marsh Sites
(Where hydrobiid snails were found.)
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<tr>
<td>RESTORED TO &lt;FULL TIDAL 1997</td>
<td>3 FT</td>
<td>1 M</td>
<td>YES</td>
<td>PERM POOL (200 M²) AND CHANNELS</td>
<td>WATERFRONT</td>
</tr>
<tr>
<td>RESTORED TO FULL TIDAL 1995</td>
<td>6 FT</td>
<td>1.9 M</td>
<td>NO</td>
<td>2M DEEP INTER-TIDAL CHANNEL</td>
<td>PT. EDITH</td>
</tr>
<tr>
<td>WITHIN PT. EDITH COMPLEX 20-50 YEARS AGO</td>
<td>½-1 FT</td>
<td>~0.50 M</td>
<td></td>
<td>1000 M²</td>
<td>WEIR TIDAL POOL</td>
</tr>
</tbody>
</table>
Fig. 2 Average salinity (ppt.), Secchi Depth/Water Clarity (cm), and Water Temperature (Celsius) at Reference and Restored Marshes 1999-2001. Inner and Outer Shell Marshes had significantly lower salinities and Inner Shell had significantly lower water clarity (secchi depths) except when compared to Tubbs Island Marsh.
Fig. 3. Densities of snails on 1 m² mesh refugia animal traps at Weir, Waterfront and Navy marshes.

Fig. 4. Densities of snails in 1/20 m² sediment traps at Weir and Waterfront Marsh Tidal Pools. (No data at Waterfront for fall 2001, fall 2002, winter 2003).
Fig. 5. Densities of snails in 25 cm² mini-quadrats on mud and algae at Weir Marsh Tidal Pool.

Fig. 6. Densities of snails in 25 cm² mini-quadrats at Weir and Waterfront Marsh Tidal Pools.
Fig. 7. Densities of snails in 25 cm$^2$ mini-quadrats out in the pool (3-5 m) and along shore at Weir and Waterfront Marsh Tidal Pools (summer 2002).

Fig. 8. Densities of juvenile snails (<0.50 mm) in 25 cm$^2$ mini quadrats on mud and algae at Weir Marsh Tidal Pool.
Fig. 9. Densities of snails by size class in 25 cm$^2$ mini-quadrats on algae at Weir Marsh Tidal Pool.

Fig. 10. Densities of snails by size class in 25 cm$^2$ mini-quadrats on mud at Weir Marsh Tidal Pool.
Fig. 11. Densities of aquatic animals in 25 cm$^2$ mini-quadrats on mud at Weir Marsh Tidal Pool.

Fig. 12. Densities of aquatic animals in 25 cm$^2$ mini-quadrats on algae at Weir Marsh Tidal Pool.