Introduction

The San Francisco Estuary (hereafter “Estuary”), which includes the San Francisco Bay (hereafter “Bay”) (Figure 1) and the Sacramento-San Joaquin Delta (hereafter “Delta”) (Figure 2), have been substantially altered by human activities (Nichols and others 1986). Habitat loss, habitat alteration, changes in water quality, invasions of alien species, and diversions of water for municipal and agricultural uses have been accompanied by declines in populations of native plants and animals. Growing conflicts between managing the Delta to enhance species of concern and managing it to provide high quality water for agricultural and urban uses led to the formation of the CALFED Bay-Delta Program (hereafter “CALFED”) in 2000, after a preliminary 5-year planning phase (CALFED 2001). CALFED is a collaborative effort among 23 state and federal agencies with the basic mission of developing and implementing a long-term comprehensive plan to restore ecological health and improve water management for the beneficial uses of the Estuary. Restoration of tidal wetlands has been proposed as an important approach to this mission. Discussions among researchers, managers, and stakeholders identified several uncertainties regarding the potential benefits of tidal wetland restoration. The articles included in this series are focused on the uncertainties considered most important to the CALFED mission. This introductory article provides background information on tidal wetlands in the Estuary and identifies the uncertainties to be addressed in the following series of articles.

Background

Around 1850, the Delta was dominated by tidal wetlands, which constituted about 87% or 1,300 km^2 of the total area (Atwater and Belknap 1980). Tidal wetlands dominated the central and southern regions of the Delta. The habitat in the northern Delta was more complex because of the formation of natural levees along channels of the Sacramento River, which isolated non-tidal wetlands from tidally influenced waters (Atwater 1982). Tidal wetlands in all areas were composed of a complex mosaic of marsh, stands of more complex vegetation, open-water pools and lakes of various sizes, mud flats, and small distributary water channels that delivered water to and from the tidal marsh in response to tidal flows. In addition, a surface area of about 100 km^2 comprised a complex network of larger river and distributary channels (including sloughs) (Atwater and Belknap 1980) that was bordered by tidal wetlands or other riparian vegetation (Atwater 1980). Recent estimates indicate that about 95% of Delta tidal wetlands have been lost, along with a significant proportion of the associated tidal sloughs (TBI 1998). Few examples of relatively pristine tidal marsh still exist. Much of the riparian vegetation bordering the larger waterways has also been lost. Large expanses of relatively deep open water that presently occur in flooded Delta islands (former agricultural islands flooded by levee breaks) were not a part of the original landscape. *Egeria densa*, an alien submerged aquatic macrophyte dominates such areas and other shallow (less than about 3.5 m) nearshore habitats (Grimaldo and Hymanson 1999). Water hyacinth, *Eichhornia crassipes*, an alien floating macrophyte may also be important in such areas, but it is largely controlled at present by application of herbicides (CDBW 2002).

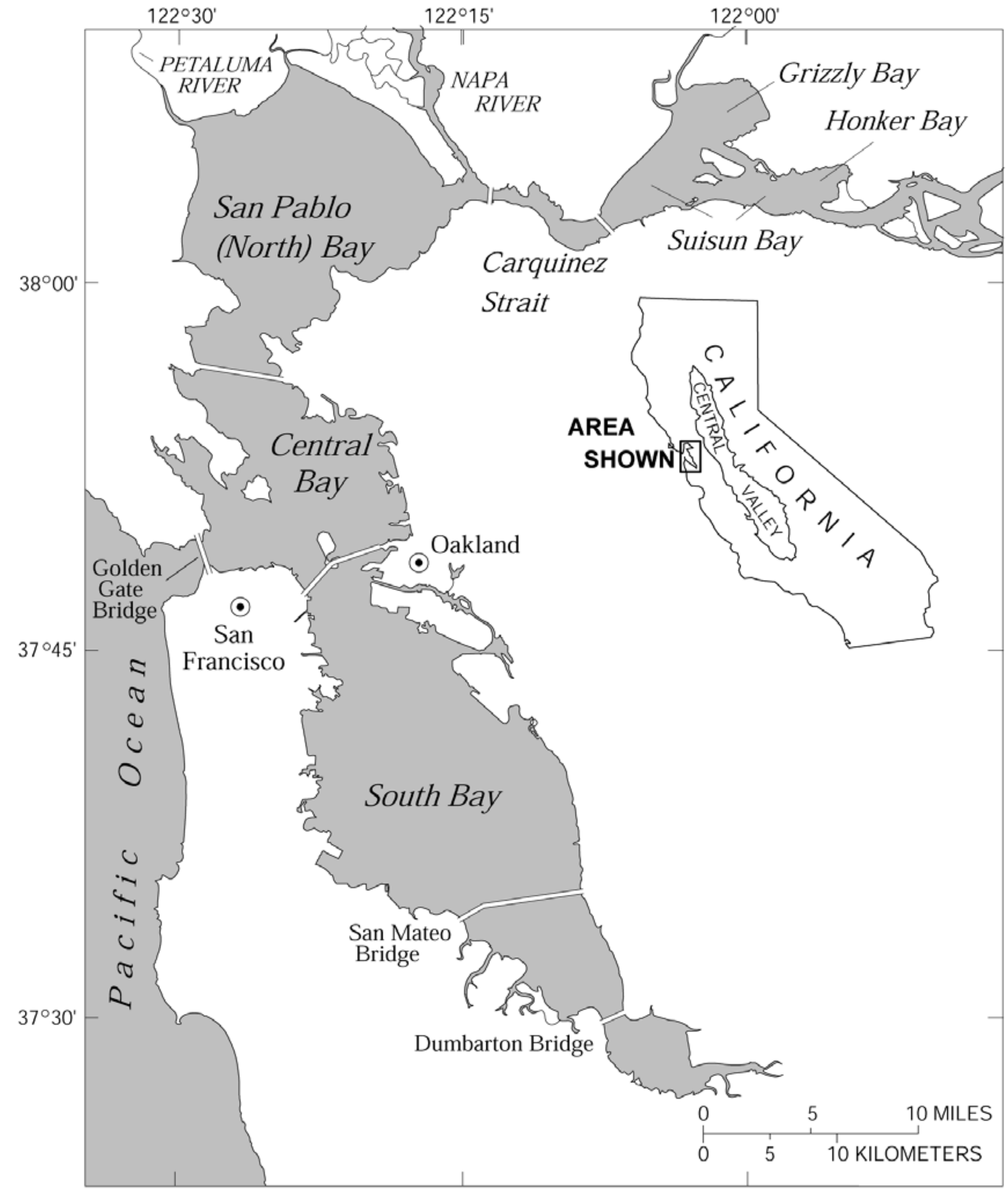

Figure 1 Areas and features within San Francisco Bay

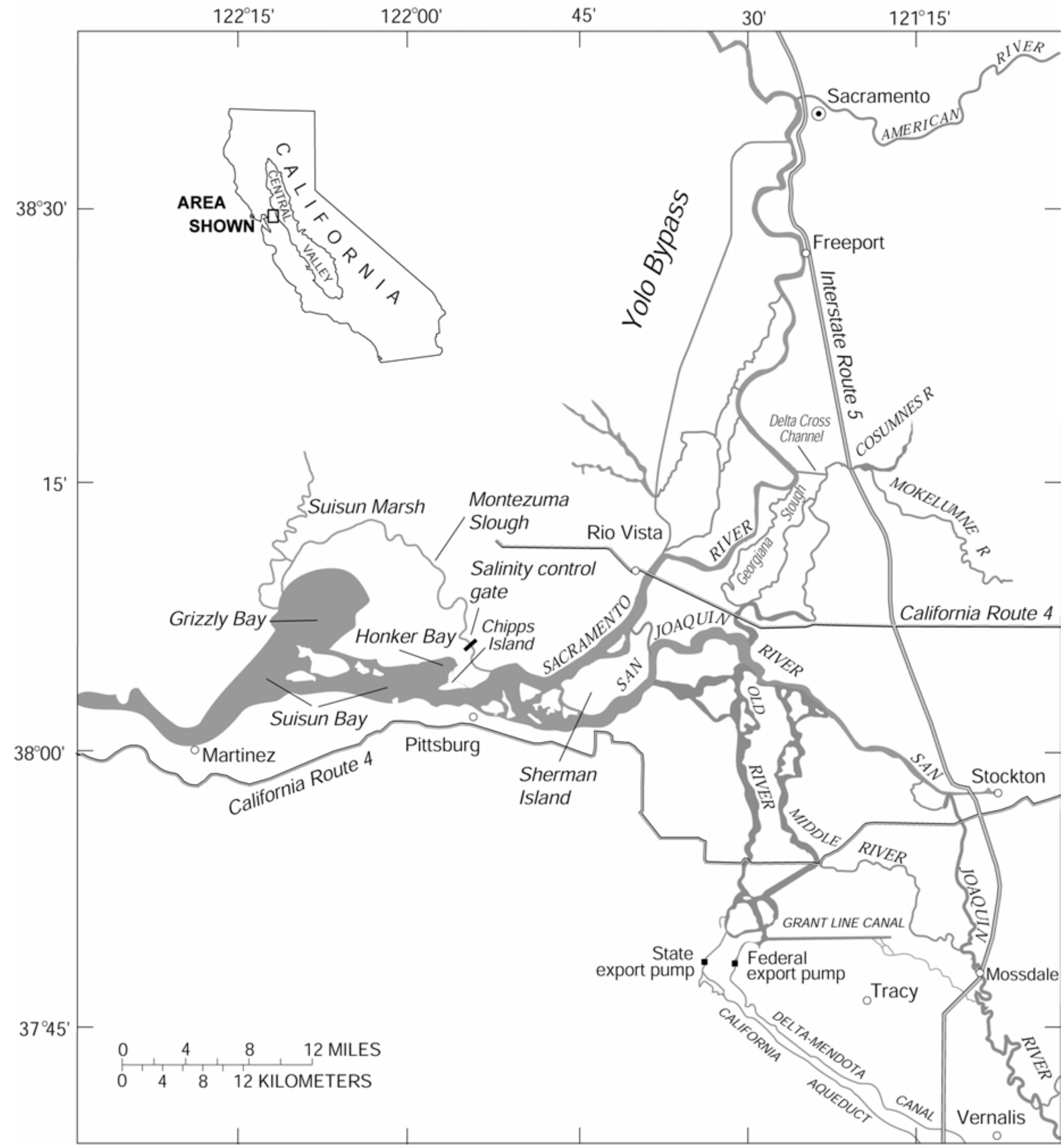

Figure 2 Areas and features within northern San Francisco Bay (west of Chipps Island) and the Sacramento-San Joaquin Delta (Delta). The Delta is approximately defined by Chipps Island to the west, Sacramento to the north, and the river confluence near Vernalis to the south.

Similarly, around 150 years ago, San Francisco Bay was bordered by about 780 km^2 of tidal marsh, concentrated in the southern half of South Bay and the northern portions of San Pablo Bay and Suisun Bay (SFEI 1998). Only about 21% of this area remains as tidal wetlands and some of those wetlands have been degraded by other land uses (SFEI 1998). For example, Suisun Marsh, with a total area of about 340 km^2, is sometimes perceived as a relatively unaltered area of tidal wetlands; however, most Suisun Marsh tidal wetlands were lost by the 1930s. Management of diked wetlands for production of waterfowl gradually replaced early agriculture in Suisun Marsh. Existing wetlands are dominated by managed wetlands (210 km^2 or 89%) with the remainder comprised of tidal wetlands (25 km^2 or 11%) (CALFED 1999). Much of the remaining tidal wetland consists of edge habitats between channels and the levees that protect managed wetlands. These edge tidal wetlands lack the marsh plains and uplands associated with natural tidal wetlands and cannot support all of the plants, animals, and ecological processes expected of natural habitats.

Historical accounts suggest that the tidal wetlands of the Estuary were highly productive, supporting large populations of aquatic and terrestrial species (TBI 1998). The diminished populations of many of the aquatic and terrestrial species in the Estuary can be interpreted as a result of the loss of critical tidal wetlands; however, declines of native species over the last few decades have taken place during a period with a limited but relatively stable area of tidal wetlands.

Other factors hypothesized to be important in the decline of Estuary species include changes in hydrology and sedimentation resulting from upstream dams and diversions (Mount 1995), changes in hydrodynamics and ecosystem processes resulting from large and small diversions within the Delta (Jassby and Powell 1994; Arthur and others 1996), effects of agricultural pesticides (Kuivila and Foe 1995), effects of trace elements resulting from industrial and agricultural activities, and the effects of invasions of alien species on native species (Carlton and others 1990; Nichols and others 1990; Alpine and Cloern 1992; Kimmerer and Orsi 1996). Water diversions and sedimentation associated with hydraulic gold mining in the late 1800s and early 1900s have been identified as important factors in the decline of anadromous fish populations in the Central Valley, particularly chinook salmon (*Oncorhynchus tshawytscha*) and steelhead rainbow trout (*O. mykiss*) (Yoshiyama and others 1998). The continuing transport of mercury from historical gold mining into the Estuary (Bouse and others 1999; Jaffe and others 1999, both personal communications, see "Notes") is a concern for both wildlife and human health.

In some cases the effects of these activities may have been interactive. For example, Herbold and Moyle (1989) suggest that hydraulic gold mining may have facilitated the success of alien striped bass and American shad in the Estuary. These species have semi-buoyant eggs that are more likely to survive in habitats with high sedimentation rates compared with many of the native species that produce benthic eggs (Herbold and Moyle 1989). The wide array of changes in the Estuary makes it extremely difficult to isolate the effects of specific factors on a particular species, especially because it is most probable that the various changes are interactive and variable in importance depending on specific circumstances (Bennett and Moyle 1996).

In support of its mission to enhance native species while providing high quality water for agriculture and human consumption, CALFED is investigating four interdependent program areas: water supply reliability, water quality, ecosystem restoration, and levee system integrity. In addition, CALFED has established a science program to guide and oversee the tasks of scientific review and adaptive management that have been identified as two of the implementation priorities of the program. The Ecosystem Restoration Program (hereafter "ERP") of CALFED investigates the ecosystem restoration program area. The mission of ERP is to implement ecosystem restoration actions to help restore and improve the health of the Estuary for all native species and some alien fishes with commercial or recreational value.

The difficulty in identifying specific causes for the declines of specific species (Bennett and Moyle 1996) is one of the reasons that ERP has focused on the concept of ecosystem restoration rather than managing individual species. This strategy assumes that management actions that reestablish natural ecosystem processes, completely or in part (such as tidal wetland restoration), will result in increased populations of desired species (native and alien) while maintaining or enhancing other beneficial uses of Estuary resources.

Objectives and Organization of the Articles

Given the tremendous loss of tidal wetlands, it is logical to assume that restoring such habitat would enhance native species; however, there is uncertainty about the extent of benefit that native species, particularly special status fishes, will derive from tidal wetland restoration. There is also concern that some results of tidal wetland restoration may not be compatible with the goals of other CALFED programs, particularly the Water Quality Program. For example, restored tidal wetlands may provide benefits for desired fishes, but may also export dissolved organic carbon to water diverted as drinking water. Disinfection of such water might result in formation of disinfection byproducts, which are a human health concern. The primary objective of each article in the series is to review the existing information, identify areas of scientific uncertainty, and suggest methods to reduce uncertainty regarding a particular issue. The issues to be addressed are stated as questions:

- Will tidal wetland restoration enhance populations of native fishes?

- Will primary production and other ecological processes in restored tidal wetlands result in net export of organic carbon to adjacent habitats, resulting in enhancement of the food web? If so, what quantities and forms of carbon are being exported? Will the carbon produced contribute to the formation of disinfection byproducts when disinfected for use as drinking water?

- Will wetland restoration actions result in increased rates of methylation of mercury? If so, is there a geographic component to the process, such that tidal wetland restoration can be targeted at geographic areas where the rates of methylation would be acceptably low?

- Will restored tidal wetlands provide long-term ecosystem benefits that can be sustained in response to ongoing physical processes, including sedimentation and hydrodynamics?

An additional question was included in the early development of this series: Are the habitat restoration needs of aquatic and terrestrial species of concern to CALFED compatible, within the context of tidal wetland restoration? During the development of this series, the effort on this question evolved into the development of a monitoring program "Terrestrial and Amphibious Monitoring Program" rather than a technical review of the available information and assessment of uncertainties. Given the different objectives of this effort, a paper was not prepared on the topic for this series, but substantial information has been developed (Atkinson and others 2002).

For the purposes of these articles, the term "tidal wetland" includes wetland areas subject to the natural tidal cycle. Passively or actively managed wetlands, such as duck club ponds, are not explicitly included. Such habitats will be discussed as necessary for understanding of tidal marsh processes. Floodplains are also not explicitly considered, except as necessary to discuss their interactions with tidal wetlands. The articles will consider nearshore aquatic habitats, including intertidal and subtidal areas of submerged aquatic vegetation and open water. In general, this aquatic zone includes the area referred to as "shallow water habitat" and can be roughly defined as water less than 2 m deep at mean lower low water. Discussion of such areas is necessary to understand connections of tidal wetlands to more open water habitats of the larger channels and bays.

The geographic scope of the articles generally corresponds to the distribution of proposed CALFED tidal wetland restoration actions (CALFED 1999). The major focus is the legally defined Sacramento-San Joaquin Delta and Suisun Marsh with declining levels of emphasis on tidal wetlands surrounding Suisun Bay, northern San Francisco Bay (San Pablo Bay), and the combined Central Bay and South Bay.

Each article is structured somewhat uniquely but includes a review of the current scientific understanding of the issue, one or more conceptual models summarizing the current understanding, and a discussion of approaches to address sources of uncertainty. All of the articles cite non-peer-reviewed reports or manuscripts. In some cases, this is the only information available. In other cases, the referenced information is so new that the relevant manuscripts have not yet received scientific peer review. The articles are intended as a useful presentation of information and ideas for a wide range of scientists, resource managers, and interested stakeholders. Reducing the uncertainty surrounding these issues is of critical importance because tidal wetland restoration is assumed to be a critical action for enhancement of special status species and general recovery of ecosystem processes.

Acknowledgements

Larry Smith, Wim Kimmerer, Denise Reed, Randy Brown, Fred Nichols, Michael Fainter, Kim Taylor, Sam Luoma and numerous others supported the development of this series of articles. Comments by Fred Nichols and Randy Brown significantly improved the manuscript. The CALFED Bay-Delta Program provided support for this article.

References

Alpine AE, Cloern JE. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnology and Oceanography 37:946-55.

Arthur JF, Ball MD, Baughman SY. 1996. Summary of federal and state water project environmental impacts in the San Francisco Bay-Delta Estuary, California. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem, further investigations into the natural history of San Francisco Bay and Delta with reference to the influence of man. San Francisco (CA): Pacific Division, AAAS. p 445-95.

Atkinson A, Marn C, Fong B, editors. 2002. Terrestrial and amphibious monitoring plan for the CALFED Bay-Delta Program: workshop summaries for summer, 2000. Final report to CALFED.

Atwater BF. 1980. Distribution of vascular-plant species in six remnants of intertidal wetland of the Sacramento-San Joaquin Delta, California. Menlo Park (CA): U.S. Geological Survey. U.S. Geological Survey Open-File Report 80-883.

Atwater BF. 1982. Geologic maps of the Sacramento-San Joaquin Delta, California. Menlo Park (CA): U.S. Geological Survey. U.S. Geological Survey MF-1401. 20 sheets.

Atwater BF, Belknap DF. 1980. Tidal-wetland deposits of the Sacramento-San Joaquin Delta, California. In: Field WE, Bouma AH, Colburn IP, Douglas RG, Ingle JC, editors. Quaternary depositional environments of the pacific coast: pacific coast paleogeography symposium 4. Proceedings of the Society of Economic Paleontologists and Mineralogists. Los Angeles (CA): Society of Economic Paleontologists and Mineralogists.

Bennett WA, Moyle PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem, further investigations into the natural history of San Francisco Bay and Delta with reference to the influence of man. San Francisco (CA): Pacific Division, AAAS. p 519-42.

[CALFED] CALFED Bay-Delta Program. 1999. CALFED Bay-Delta Program ecosystem restoration program plan, vol. II: ecological management zone visions. Sacramento (CA): CALFED Bay-Delta Program. p 159.

[CALFED] CALFED Bay-Delta Program. 2001. CALFED Bay-Delta Program annual report 2001. Sacramento (CA): CALFED Bay-Delta Program. Accessed on 16 Jul 2000. Available at: http://calwater.ca.gov/aboutcalfed/annualreport2001.shtml Additional CALFED information available at: http://calwater.ca.gov/

Carlton JT, Thompson JK, Schemel LE, Nichols FH. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam, *Potamocorbula amurensis*. 1. Introduction and dispersal. Marine Ecology Progress Series 66:81-94.

[CDBW] California Department of Boating and Waterways. 2002. Aquatic pest control water hyacinth and *Egeria densa*. Accessed on 17 Jul 2000. Available at: http://www.dbw.ca.gov/aquatic.htm

Grimaldo L, Hymanson Z. 1999. What is the impact of the introduced Brazilian waterweed *Egeria densa* to the Delta ecosystem? Interagency Ecological Program Newsletter 12(1):43-5. Accessed on 16 Jul 2000. Available at: http://www.iep.water.ca.gov/report/newsletter

Herbold B, Moyle PB. 1989. The ecology of the Sacramento-San Joaquin Delta: a community profile. Washington, DC: United States Fish and Wildlife Service. United States Fish and Wildlife Service Biological Report 85.

Jassby AD, Powell TM. 1994. Hydrodynamic influences on interannual chlorophyll variability in an estuary: upper San Francisco Bay-Delta (California, USA). Estuarine, Coastal and Shelf Science 39:595-618.

Kimmerer WJ, Orsi JJ. 1996. Changes in the zooplankton of the San Francisco Bay Estuary since the introduction of the clam, *Potamocorbula amurensis*. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem, further investigations into the natural history of San Francisco Bay and Delta with reference to the influence of man. San Francisco (CA): Pacific Division, AAAS. p 403-24.

Kuivila KM, Foe CG. 1995. Concentrations, transport and biological effects of dormant spray pesticides in the San Francisco estuary, California. Environmental Toxicology and Chemistry 14:1141-50.

Mount JF. 1995. California rivers and streams. Berkeley (CA): University of California Press.

Nichols FH, Cloern JE, Luoma SN, Peterson DH. 1986. The modification of an estuary. Science 231:567-73.

Nichols FH, Thompson JK, Schemel LE. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam, *Potamocorbula amurensis*. 2. Displacement of a former community. Marine Ecology Progress Series 66:95-101.

[SFEI] San Francisco Estuary Institute. 1998. Bay Area EcoAtlas, version 1.50. Oakland (CA): San Francisco Estuary Institute. Accessed on 17 Jul 2002. Available at: http://www.sfei.org/ecoatlas/index.html

[TBI] The Bay Institute. 1998. From the Sierra to the sea. San Rafael (CA): The Bay Institute of San Francisco. 280 p.

Yoshiyama RM, Fisher FW, Moyle PB. 1998. Historical abundance and decline of chinook salmon in the Central Valley Region of California. North-American Journal of Fisheries Management 18:487-521.

Notes

Bouse RM, Hornberger MI, Luoma SN. 1999. Mercury-contaminated hydraulic gold-mining debris in San Francisco Bay. Presented at Geological Society of America Cordilleran Section centennial meeting, 2-4 June 1999, Berkeley, CA.

Jaffe BE, Smith RE, Cappiella K, Bouse R, Luoma S, Hornberger M. 1999. Mercury-contaminated hydraulic mining debris in north San Francisco Bay–a legacy of the Gold Rush. Presented at Geological Society of America Cordilleran Section centennial meeting, 2-4 June 1999, Berkeley, CA.