Fish and large-scale change in the San Francisco Estuary, California: towards a more sustainable future

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Summary. The San Francisco Estuary supports a diverse fish fauna in which key species are in severe decline. The estuary is faced with catastrophic structural and ecological changes, especially in the Delta and Suisun Marsh, as the result of anticipated levee failure caused by the combination of earthquakes, land subsidence, sea level rise, and increased high outflows events (from climate change). The resulting flooding of Delta islands and Suisun Marsh is predicted to disrupt California's water supply system and, consequently, the state's economy. From a fish perspective, the changes are likely to create conditions in which desirable species can persist at least at present low levels, after a period of possible high mortality created by the initial flooding events. Taking actions to regulate ecological changes in the estuary *before* the disaster could actually improve conditions for desirable fishes while being highly compatible with delivering services the Delta provides, especially water supply. Specific actions include improving habitat for fish in Suisun Marsh, Cache Slough, the Yolo Bypass, and the San Joaquin River, while creating islands in which flooding can be managed. The key is increasing habitat heterogeneity over present and now-likely future conditions. No matter what actions are taken there will be a high degree of uncertainty as to their ecological benefits but the present situation in estuary represents an unprecedented opportunity to reverse the impacts of over 150 years of negative ecological change.

Introduction

The San Francisco Estuary (SFE) is the largest estuary on the west coast of North America and one of the most altered (Nichols et al. 1986). It is highly urbanized but contains extensively diked agricultural lands and marsh habitats. It is also highly invaded by alien species, especially the aquatic habitats. Not surprisingly, the native species of plants and animals have declined in abundance; several are extinct and others are listed as threatened or endangered under state and federal laws (Herbold et al. 1992). Human caused changes to the SFE are still taking place at an accelerated rate and there are strong indications that major, catastrophic changes to the SFE are imminent (Mount and Twiss 2005; Lund et al. 2007). The changes are likely to be most dramatic in the upper part of the estuary, the Sacramento-San Joaquin Delta (the Delta), where large-scale levee failure can seriously disrupt local, regional, and state economies. A principal concern is disruption of California's water distribution system. Much of the fresh water used by San Joaquin Valley farms and the vast urban areas of southern California originates (directly or indirectly) from the estuary's inflowing rivers. This water is pumped from the Delta by the State Water Project and the federal Central Valley Project. Additional water is removed to supply aqueducts to cities around San Francisco Bay and to water farms in the Delta. Large scale flooding could also eliminate farming in thousands of acres of island land, threaten urban areas, and disrupt railroads, pipelines, and other infrastructure (Lund et al. 2007, available on line at ***PPIC.org***). Likewise, a sudden catastrophic change to the Delta and SFE will affect already declining native species and encourage the further spread of alien species.

A major question being asked by management agencies and regional stakeholders is "how can we prevent large-scale change from taking place in the SFE, especially the Delta?" Answering precursors to this question (mainly, how do we protect endangered fish and fisheries?) was one of the reasons for the establishment of CALFED in 1996, a massive joint state-federal management and research effort (http://calwater.ca.gov/) which has been criticized for not quickly solving the problems of the SFE (Little Hoover Commission 2006). A report produced by the University of California, Davis and the Public Policy Institute of California (Lund et al. 2007) turned the original question on its head, asking instead "How can the Delta be managed to accommodate large-scale change before undesirable changes are forced by catastrophic events?" In this essay, key findings of Lund et al. (2007) are summarized in relation to aquatic organisms, especially fish. I first describe the SFE, provide a brief introduction to the fish fauna, and then discuss the major drivers of change. I then describe what is likely to happen to key fish species if present management trends continue, followed by suggestions for major actions that could be taken to improve the SFE for fishes even in the face of large-scale change.

The San Francisco Estuary

The SFE is the outlet of the Sacramento and San Joaquin Rivers, which in turn drain much of central California. A primary source of the water for the rivers is the Sierra Nevada, which intercept moisture-laden clouds coming off the Pacific Ocean. The estuary has three distinct segments, San Francisco Bay (including San Pablo Bay), Suisun Bay and Marsh, and the Sacramento-San Joaquin Delta (Figure 1). Each segment has a confined outlet through which the tides surge back and forth, creating complex hydrodynamics: the Golden Gate (San Francisco Bay), the Carquinez Straits (Suisun Bay), and the river confluence at Sherman Island (Delta), respectively. These narrows have allowed the three regions to have distinct identities, emphasized by human modifications to them. The Delta is perceived as region where fresh water from the rivers tidally sloshes back and forth in leveed channels, flowing between islands of agricultural fields. The islands are highly subsided (many are 5+ m below sea level), surrounded by 1800 km of fragile levees made of local materials, often peat. Historically, the Delta was a vast marshland that was flooded annually by undammed rivers (Lund et al. 2007).

Suisun Bay, in contrast was, and still is, a large area of open water that is transitional between the fresh waters of the Delta and the salt waters of San Francisco Bay; it is a shallow region of wind-stirred, brackish water, lined with tidal marshes. The largest of these marshes, in fact nearly as large as Suisun Bay itself, is Suisun Marsh. This 30,000+ ha marsh is largely managed today as freshwater marsh, mostly for duck hunting in both private duck clubs and public wildlife areas. The key for maintaining its freshwater character is inflow from the Sacramento River via Montezuma Slough. Montezuma Slough has large tidal gates on its upper end which control salinity in the marsh by allowing fresh water to flow in but prevent the tides from pushing it back out again. Over 360 km of levees separate the marsh islands from the tidal channels, in which water is still seasonally brackish. The channels are highly productive of fish, however, which are a mixture of freshwater and marine species (Matern et al. 2002).

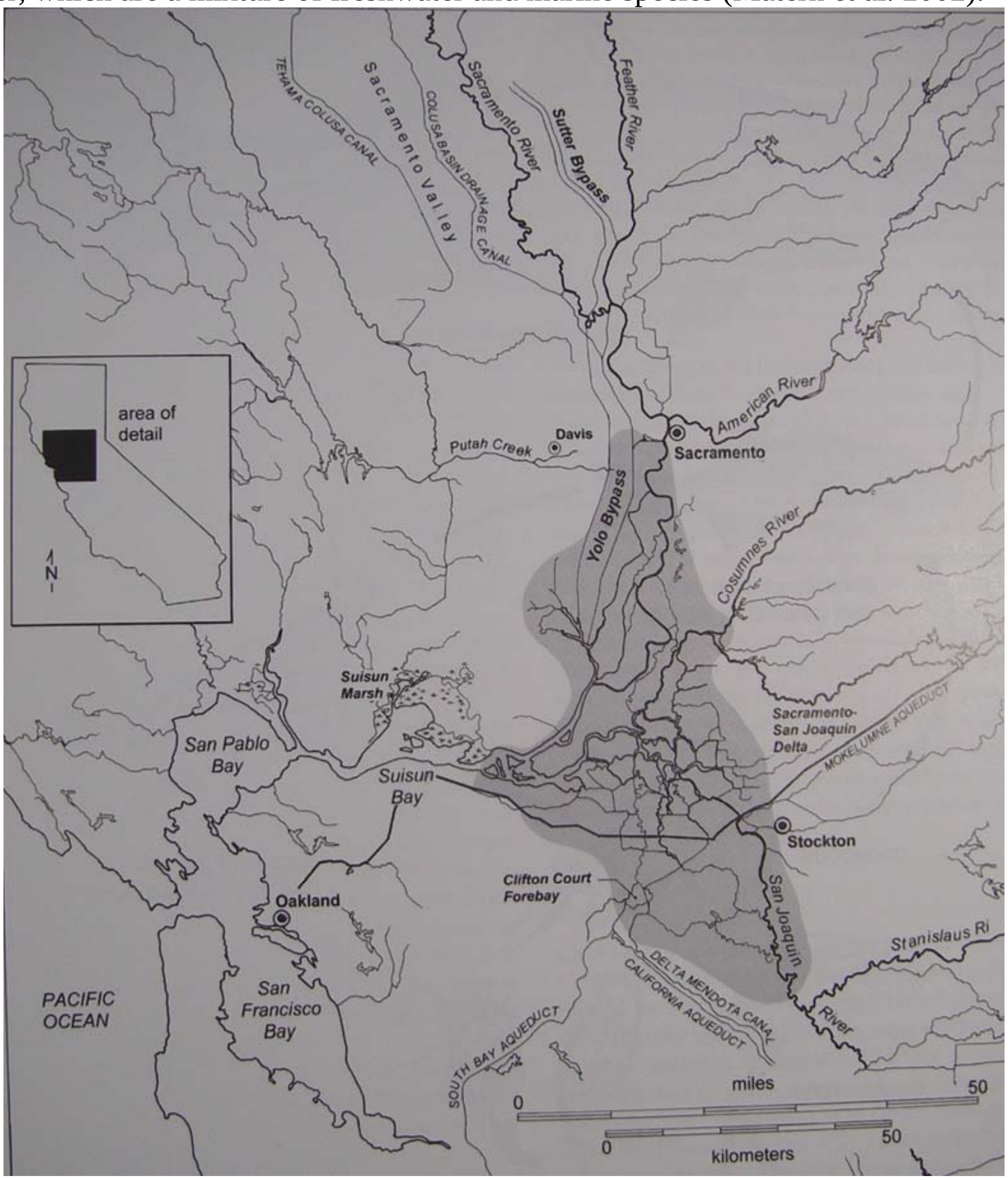

Figure 1. The San Francisco Estuary, showing the extent of the legal Delta and other key features. From Moyle (2002).

The marine species in Suisun Marsh come from San Francisco Bay, which is largely a saltwater system, with variable but high salinities; the actual salinity value depends on location and season. San Francisco Bay is ringed by cities and its fringe marshes are fragments of its original tidal marsh system.

All three parts of the SFE were once more variable in their salinities and river-driven hydrodynamics than they have been for the past 50-60 years (Bay Institute 1998). During wet years, the spring snow-melt from the Sierra Nevada could temporarily make fresh the surface waters of San Francisco Bay, while during late summer of drought years ocean salt could be detected at the upper ends of the Delta (DWR 1993), especially once agriculture diverted large amounts of water. The advent of the federal Central Valley Project and the State Water Project, however, allowed the system to stabilize, so that, for the purposes of policy and public perception, the Delta and Suisun Marsh became permanent freshwater systems, Suisun Bay became a brackish water system, and San Francisco Bay became an exclusively marine system. The two water projects (and other related projects) constructed huge dams on the Sacramento and San Joaquin rivers and all their major tributaries in the 1930s-1960s, with such perverse consequences as increasing the summer flows of the Sacramento River and drying up the San Joaquin River. The dams allowed for the regulation of salinity in the upper SFE. By releasing large quantities of water, especially in the summer, the dam operators could both keep salt water out of the Delta and Suisun Marsh and permit the pumping of the water, from the southern edge of the Delta, for agricultural and urban use.

For further information on the environmental and ecological history of the SFE see Herbold et al. (1992), Hollibaugh (1996), Bay Institute (1998), and Lund et al.. (2007) or see http://www.deltavision.ca.gov. The rest of this essay will focus primarily on the Delta and Suisun Bay and Marsh, because the lowermost part of the SF Estuary, San Francisco Bay, has a whole additional set of problems related to its intense urbanization.

The Fishes

SFE has a high diversity of fishes, representing marine, freshwater, anadromous, and estuarine species, as well as native and alien species (Matern et al. 2002, Moyle 2002). About 75 species, largely marine, are known from SF Bay in recent years, of which only 5 are alien species. In Suisun Marsh and Bay, 53 species are known, a mixture of marine, freshwater, and anadromous (sea-run) species. They represent 28 native species and 25 aliens (Matern et al. 2002). In the Delta, there are about 46 regularly occurring species, a mixture of freshwater and anadromous fishes, of which 27 are aliens. The total fish fauna consists of about 120 species that can be found in one environment or another on a fairly regular basis, of which about 30 (25%) are aliens, mostly in fresh and brackish water. The invasion of alien species has accompanied past large-scale environmental change and has been a driver of declines of native species, including extinctions of native species such as thicktail chub and Sacramento perch (Moyle 2002, Marchetti and Light 2007). Changes over the past 50 years, since the advent of the major water projects, have led to severe declines of most native species, including four runs of Chinook salmon and the delta smelt. This result has been that five fishes, including delta smelt and two runs of Chinook salmon, are currently listed as threatened or endangered by state and federal governments (Moyle 2002). In more recent years, declines in fisheries have also been of major concern, especially of fall-run Chinook salmon, white sturgeon, and alien striped bass. Some of the fishes most likely to affected by future large scale changes to the SFE and also likely to drive policy decisions are listed in Table 1.

Species	Native?	Why important (status)	comments
Delta smelt *Hypomesus transpacificus*	yes	T&E species, endemic	Open water pelagic, near extinction
Longfin smelt *Spirinchus thaleichthys*	yes	Special concern species	Open water pelagic, in severe decline
Splittail *Pogonichthys microlepidotus*	yes	Special concern species, endemic	Spawns on floodplains, rears in brackish water
Tule perch *Hysterocarpus traski*	yes	Native, declining	Represents complex of native fishes
Sacramento perch *Archoplites interruptus*	yes	Extirpated	Reintroduction program proposed
Striped bass *Morone saxatilis*	no	Estuarine sport fish. declining	Pelagic, uses entire estuary
White sturgeon *Acipenser transmontanus*	yes	Sport fish, declining	Anadromous, rears in estuary
Southern Green sturgeon *A. medirostris*	yes	Endemic, threatened	Anadromous, rears in ocean
Chinook salmon *Oncorhynchus tshawytscha*	yes	Four runs, all in decline	Anadromous
Chinook salmon, spring run	yes	threatened	Appears in estuary mainly as smolts
Chinook salmon winter run	yes	endangered	Appears in estuary mainly as smolts
Chinook salmon fall run	yes	Sport and commercial fisheries, hatchery driven	Large numbers of fry in estuary but survival low
Largemouth bass *Micropterus salmoides*	no	Alien predator, game fish, Increasing in abundance	Represents complex of alien pond fishes in Delta
Threadfin shad *Dorosoma petenense*	no	Locally abundanct but in decline	Regarded as part of Pelagic Organism Decline

Table 1. Fish species that of major importance for management in the San Francisco Estuary. Information from Moyle (2002).

Drivers of Change

The major drivers of change in the SFE that are together or individually likely to result in major shifts in environmental conditions, including catastrophic shifts are: earthquakes, island subsidence, sea level rise, climate change, and invasions of new alien species (Lund et al. 2007). Human land and water use could arguably be listed as another driver of change but these uses are strongly affected by the first five drivers (i.e., are the reason the first five are of concern) so will not be treated further as drivers here. The major catastrophic consequence of the five major drivers is extensive levee failure in the Delta and Suisun Marsh. From an ecological perspective, the consequence is sudden change of in the hydrodynamics of the two regions as the islands fill with water, creating new habitat conditions, followed by invasions of undesirable species into the new habitat space.

Earthquakes. There are at least five faults in the Delta region but there have been no major earthquakes in the region since the great 1906 San Francisco Earthquake. This means that pressure is building up on the faults, steadily increasing the probability that one will move as time goes by (Mount and Twiss 2005). The major impact likely from earthquakes is collapse of levees in the Delta and Suisun Marsh because of their poor foundation soils and weak construction.

Island subsidence. The islands of the Delta were originally marshlands on a thick base of peaty soils. Over 182,000 ha of islands were diked and drained for farming in the 19th century and soils were typically burned annually to release nutrients from the peat, causing the interiors of the islands to subside rapidly. Even after burning stopped subsidence continued through oxidation of plowed soils and dust carried off by the frequent winds. As a result, all islands with peat soils used for farming have subsided, with subsidence greatest (3-7 m below sea level) in west and central Delta (Figure 2). Subsidence continues as long as farming continues. The effect of subsidence is to create a series of depressions surrounded by water, which will pour in if given the chance to break through the levees.

Sea level rise. Sea level is rising in the SFE and has been for at least thousands of years. Because of global warming, the rate of rise is accelerating. There is scientific debate about how rapidly and how much sea level will continue to rise, but a 30-50 cm rise in the next 50 years is plausible. The higher mean sea levels result in much higher high tide levels, increasing the probability that levees in the Delta and Suisun Marsh will overtop and then collapse, especially if combined with flood flows coming down the rivers.

Climate change. The climate of California is becoming significantly warmer, a trend that is likely to continue for some time (Dettinger 2005). While average precipitation is not expected to change much, more will fall as rain and less as snow in the high mountains. Year to year variability in rainfall is also expected to increase, as will the frequency of extended droughts and big floods. Once result of this change is increased hydrostatic pressure on levees during storms and floods and increased likelihood of failure.

Invasive species. The SFE has the reputation of being the most invaded estuary in the world and new invasions continue at a high rate of frequency (Cohen and Carlton 1998). Recent invaders (e.g.,overbite clam, Brazilian waterweed) have already had major impacts on ecosystem structure and function. New invaders or expanding populations of existing invaders are likely to take advantage of the new habitats created by large-scale levee failure (Marchetti and Light 2007), further exacerbating the effects of levee failure and increasing the difficulty of protecting native species.

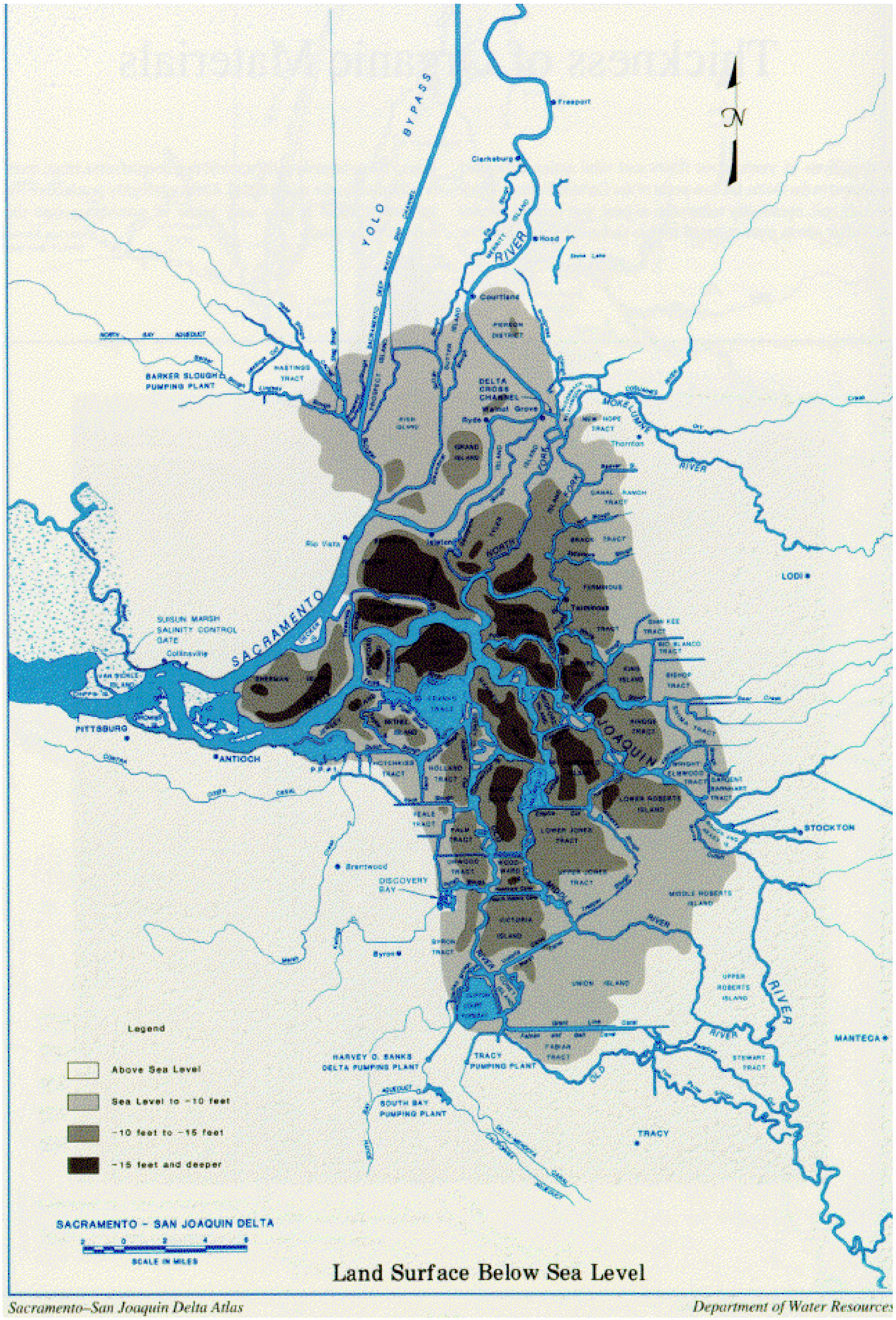

Figure 2. Map of the Sacramento-San Joaquin Delta showing land subsidence. From DWR (1993). Recent surveys indicate that subsidence in most areas is 1-5 ft greater than shown (DWR, unpublished data).

Ecological effects of large-scale change

The likelihood is high that two or more of the above drivers of change will act together to create catastrophic levee failure and other changes within the next 50 years (Mount and Twiss 2005; Lund et al. 2007), assuming the SFE continues to be managed as it is today. The probability of such an event is high enough so that it is presumably more a matter of "when" and "how much" rather than "if." In recognition of this, the Delta Risk Management Strategy (DRMS) team of the California Department of Water Resources has modeled the effects of up to 50 simultaneous levee breaches on Delta islands (http://www.drms.water.ca.gov). Other signs of high levels of interest include (1) the appointment by Governor Arnold Schwarznegger in February 2007 of the Delta Vision Committee with a Blue Ribbon Task Force to find ways to prevent or reduce the impacts of the impending disaster, (2) the recent passage of bond issues to fix levees and other infrastructure affecting urban areas,(3) the establishment of a Bay-Delta Conservation Plan process and (4) numerous other actions and processes by agencies at all levels of government. The scenario of most concern is simultaneous and cascading failures of levees throughout the Delta because of the impact of such failures on southern California's water supply, on agriculture and other uses of Delta islands, and on urban areas in and around the Delta (Lund et al. 2007). Here, however, we discuss mainly the impacts on the ecosystems of the Delta and Suisun Marsh, especially with respect to fish.

Delta. For the central and western Delta, the basic 'disaster' scenario is that following multiple levee failures, water would rush in, filling as much as 2.5 *billion* cubic meters of space in the island basins. If the levee collapses occurred as the result of the combination of high outflows and high tides, the islands would likely fill mostly with fresh water. If the levee collapses occurred as the result of an earthquake during a low-flow period, much of the water filling the islands would be drawn up from Suisun Bay and even San Francisco Bay creating lagoons with varying degrees of salinity

The open-water habitat thus created would be up to 10 m deep and subject to strong tidal currents, as well as mixing from frequent winds. The hydrodynamic and salinity regimes of each flooded island would depend on the number and location of levee breaches, closeness of the area to Suisun Bay (source of salt water) and to inflowing rivers, and relationship to infrastructure such as the ship canal that goes through the system. As levees continued to erode, many of the flooded islands would presumably come to resemble Frank's Tract, a large island in the central Delta that flooded in the 1930s and was left that way. It is currently freshwater lagoon with complex hydrodynamics that is dominated in summer by dense growths of Brazilian waterweed, *Egeria densa.*

Presumably, the flood water would initially be highly turbid from the disturbance of peat and sediment on the islands (DWR 2007) but once the suspended material had settled there would be massive blooms of algae because of the release of nutrients from the soils and the increased water transparency. Depending on the species making up the algal blooms (diatoms vs green algae vs cyanobacteria), a bloom of zooplankton should quickly follow. Within a year, island lagoons with brackish water lagoons would be heavily colonized by the overbite clam, an alien species which currently dominates the benthos of Suisun Bay. Presumably, the clams would then consume much of primary production and carbon of the new lagoons, as they do in Suisun Bay, reducing zooplankton populations. Island lagoons that contain fresh or low salinity water, would likely be colonized in 1-2 years with the species that dominate similar areas in the Delta: Brazilian waterweed and, in areas with sufficient flow, Asian clams. The combination would result in lagoons choked with weeds, with low zooplankton populations (like Frank's Tract today). It is possible that flooded islands located close to both sources of freshwater inflow (Sacramento River) and tidal sources of salt water could maintain a pool of water that would fluctuate enough in salinity on either an annual or interannual basis to keep either the overbite clam or Brazilian waterweed-Asian clam from becoming dominant. Biomass production in such lagoons would be concentrated in a pelagic system of phytoplankton, zooplankton, shrimp, and fish, such as was the case of Suisun Bay before the invasion of overbite clam in the 1980s. Obviously, these scenarios can all be strongly affected by local conditions of wind, tide, and river, as well as the diverse configurations of the lagoons (which will change constantly as levees deteriorate after the initial breeches).

Suisun Marsh. Suisun Marsh, for the most part, is not subsided as much as the Delta, although much of it is 0-2.3 m below sea level (which is rising) and some (ca. 16%) is more than 2.3 m below sea level (C. Enright, DWR, pers. comm.). Before European settlement it was high marsh, mostly flooding on high tides and high river flows. A scenario of wide-scale levee failure in the Delta is likely to include Van Sickle Island, located at the entrance to Montezuma Slough, the main artery of the Marsh. Van Sickle Island is already subject to frequent levee failures, although failures are quickly repaired. The rapid repair response (by public agencies) occurs in good part because if the island floods, the entire freshwater distribution system of the central Marsh (Roaring River Slough) ceases to work efficiently and the southern third of the Marsh (between Montezuma Slough and Suisun Bay) becomes tidal and brackish. Future failure will likely make much of the central Marsh tidally brackish. Less dramatically, increasingly high tides (from sea level rise) and increasingly large flood events (from climate change) are likely to cause levee over-topping and failures within the Marsh at increasing rates. Thus the ultimate fate of much of Suisun Marsh is to be inundated with tidal waters and to become a tidal brackish-water marsh, with seasonally higher salinities in many areas than were historically present. Much of it is likely to be permanently inundated. How the future marsh will actually look will depend on the interactions of a number of factors: (1) the rapidity and extent of sea level rise, (2) the depth of tidal and other flooding, (3) the residence time of the water in different areas i.e. the relationship between the flooded areas and the deeper channels/sloughs that drain them, (4) response of the natural vegetation to the inundation and salinity gradients, and (5) the influence of existing artificial dikes and channels, including railroad and road beds. This future Marsh, however, will certainly have a mosaic of habitats including, most importantly, extensive tidal brackish water marsh areas. These areas will be drained by channels that should gradually recover their historic dendritic nature and be kept open by strong tidal action.

Effects on fishes of large-scale change

In the broadest sense, the creation of more aquatic habitat in the Delta and Suisun Marsh will be good for fish, resulting in a net increase in numbers and biomass, once the initial flooding period is past. The important question is what will happen to the species that people care most about (Table 1). These are native species that are listed as threatened or endangered or are in severe decline or fishes that support fisheries. The effects suggested in the following accounts are highly speculative, but based on extensive knowledge of the fishes, which are well studied (Moyle 2002, see also recent review papers by various authors in the on-line journal *San Francisco Estuary and Watershed Science*).

Delta smelt. The single most important species from the viewpoint of affecting management of water in the Delta is the delta smelt, which is listed as threatened by both state and federal governments and is on the verge of extinction (Bennett 2005). It has a one-year life cycle, is a pelagic planktivore, and is endemic to the SFE, spawning in the Delta and rearing in Suisun Bay and Marsh (Moyle 2002, Bennett 2005). It is highly likely that most delta smelt will be sucked into the rapidly filling islands under multiple levee breach scenarios, whether they were upstream spawning in the upper Delta, downstream rearing in Suisun Bay, or moving between the habitats. A few smelt might be able to avoid the displacement if they were located in the distant peripheral habitats such as the mouth of the Napa River, Montezuma Slough, or Cache Slough in the north Delta. The DRMS study (DWR 2007) predicts that many, if not most, fish sucked into the flooding islands will die of stress, especially that created by particulate matter in the water abrading gills and creating high turbidity. The delta smelt, as a small (< 9 cm TL) delicate, mid-water, visual feeder, would seem especially vulnerable to these conditions. Unfortunately, data is lacking to support the high turbidity mortality hypothesis. Previous levee breaches on single islands have not been accompanied by reports of fish kills, but no one was looking in the haste to repair the levees and pump out the islands. It seems unlikely, however, that a complete fish kill would result from filling process, given the volumes of water involved and the nature of the matter (organic matter, mainly peat particles) most likely to be suspended. The filling would be most disastrous for Delta smelt if they were spawning because it would suck them away from suitable spawning areas and would likely create hydrodynamic conditions (diminished tidal range in channels) that would make return difficult. Likewise, surviving larval smelt would likely find unfavorable conditions for feeding in the newly filled islands and could starve before large populations of microzooplankton (especially rotifers) developed.

Assuming massive blooms of toxic algae (e.g., *Microcystis*) do not occur, a month or so after island filling and hydrodynamic stabilization, conditions for plankton feeding fish such as smelt should start becoming favorable with the development of blooms of one or more species of small food organisms. Delta smelt that survived up to this period in the islands should then find conditions extremely favorable for growth and survival, especially in islands that maintained salinities of < 2 mg/l and temperatures of <20°C. Thus impact of a large-scale levee breach event on delta smelt depends in good part on the timing of the event. Presumably, a higher proportion of the population would be able to survive an event in July- November, than in December-June.

In the long run, however, permanently flooded islands in the right place could *increase* the amount of favorable habitat for delta smelt. If a flooded island had conditions (mainly fluctuating salinity) that excluded dominant invasive benthic species, it would likely become highly productive pelagic habitat, habitat which is apparently in short supply for smelt at times today (Bennett 2005, Hobbs et al. 2006, 2007). Delta smelt would presumably also benefit from a flooded Suisun Marsh as rearing habitat, if flooding increased productivity of intersecting channels, especially Montezuma and Suisun sloughs, and salinity fluctuations reduced the impacts of invasive species.

One indirect positive effect for smelt of large-scale island flooding would be that the large pumps of the State Water Project and the federal Central Valley Project in the South Delta would be shut down for long periods of time because of salty water at their intakes. Because in some years pumping from the two plants can negatively affect delta smelt populations through entrainment and other effects (Bennett 2005), shutting down the pumps will remove one potential major source of mortality, perhaps compensating for some of the flooding mortality.

Longfin smelt. Longfin smelt have a 2-3 year life cycle, much of which is spent in San Francisco Bay and/or the Gulf of the Farallons, outside the Golden Gate (Moyle 2002, J. Rosenfield, unpublished analysis). They spawn in the western Delta in winter and often spend the first year of their life in Suisun Bay and Marsh. Being anadromous and iteroparous with multiple age classes, they are less vulnerable to extirpation by a large-scale event than are delta smelt. Like delta smelt and other planktivores, however, longfin smelt have suffered a large decline in their population in recent years. Thus large scale levee collapse in the Delta could initially harm longfin smelt, as indicated above for delta smelt, although a least a portion of the longfin smelt population would have reduced vulnerability because of distance from the flooded islands. For over half the year (May-November), most of adult smelt would be beyond the likely reach of a flooding event.

Permanently flooded islands in the western Delta could ultimately become important rearing habitat for larval and juvenile longfin smelt, depending on whether or not large zooplankton populations developed. Increased productivity of sloughs/channels in Suisun Marsh would presumably also benefit these smelt.

Striped bass. With high fecundity, interoparity, large size, and a life span of 40+ years, non-native striped bass have a high capacity to survive environmental disasters. Nevertheless, they have suffered a long-term decline in the SFE, although they still support a valuable fishery (Moyle 2002). In the SFE, striped bass migrate 125-200 km upstream to spawn in the Sacramento River in late April- early June. The embryos drift downstream and hatch about the time they reach Suisun Bay, where the larvae rear at low salinities. Juveniles rear throughout the estuary but seem to be most abundant in Suisun Marsh and Bay, where they feed on zooplankton. By the time they are 10 cm TL, they have largely switched to feeding on small fish. Adult striped bass are largely piscivorous and a major prey in the SFE is small striped bass. Adults will spend their entire life in the SFE, especially in San Francisco Bay, but when ocean conditions are right, some will go out into the ocean as well (Moyle 2002).

Overall, striped bass seem relatively immune to long-term effects of large-scale levee breaching. If the breaching occurred in early summer, then large numbers of larvae and juveniles could die, but in following years they could benefit from increased pelagic habitat, especially if portions of it were highly productive of zooplankton and small fish. Larger juveniles and adults are strong swimmers and could presumably quickly leave a submerged island after the initial event, assuming they survived the flooding event itself.

Sacramento splittail. Splittail are largely confined today to the SFE, where they rear in Suisun Marsh and other places with fresh to brackish water sloughs (Moyle et al. 2004). A separate population lives in the Petaluma River estuary, tributary to San Pablo Bay. Adults, which live up to 9 years, migrate up river to spawn (mostly) on floodplains in or just above the Delta (Moyle et al. 2004). Timing of spawning depends on timing of natural flooding, sometime between January and May. Juvenile splittail rear on the floodplain for a month or so and then migrate rapidly downstream to rearing areas, where they feed on benthos.

During a major island flooding event, many splittail are likely to be drawn in, although it is also likely that many others would remain in place because of living in small sloughs distant from the event and also being strong swimmers. If the levee breaching occurs in conjunction with natural high flows in January-May, large number of migrating adult or juvenile splittail could be captured. Although sudden entrainment on the flooded islands could result in high mortality, the high tolerance of splittail for poor quality (low dissolved oxygen, high turbidity, variable salinities, etc.) suggest adults and large juveniles are likely to survive the experience. The flooded islands are not likely to be great habitat for splittail until significant benthic fauna develops, especially amphipods and mysid shrimp. However, permanently flooded islands that remain brackish enough to exclude Brazilian waterweed should ultimately become suitable habitat for splittail, especially shallower areas.

*Chinook salmon***.** Four runs of Chinook salmon pass through the SFE on their way upstream to spawn in the Sacramento River: fall run, late-fall run, winter run, and spring run (Moyle 2002). All runs are depleted from historic numbers and the winter and spring runs are listed as endangered and threatened species, respectively. The fall run is supported in good part by hatchery production and occurs in tributaries to the lower San Joaquin River, as well as the Sacramento River. Fry and smolts of the salmon are found seasonally in the estuary, on their way downstream to the ocean. When the Delta was a giant tidal marsh, it was likely a major rearing area for fry before they moved out to sea as smolts. At the present time, rearing habitat for fry in the SFE is minimal and fry survival is low; higher returns of adults from hatchery fry generally occurs when the fry are planted in the SFE below the Delta (Brandes and McClain 2001, Williams 2006). Highest survival of fry and smolts in the SFE occurs in years of high outflow in both the Sacramento and San Joaquin rivers, suggesting that it pays the fish to move through the Delta rapidly. Survival of fry and smolts is also highest when the fish are largely confined to the main river channels and do not get moved into the Central Delta (Brandes and McClain 2001). Although juvenile salmon can be captured in SFE at almost any time of year, most movement is in December through April.

As with other fish, the immediate effect of a major levee failure in the Delta depends on the time of year in which it occurs, with the greatest impact likely to be in February –April, assuming migrating juvenile salmon, especially fry, sucked into the flooded islands would mostly die. The effect would be greater for San Joaquin River salmon than for Sacramento River fish because there would more likely be a continuous river channel for the fish to follow on the Sacramento side, due to location and greater flows. Once the island lagoons had become established, they would generally be unfavorable habitat for juvenile salmonids because they would contain little of the shallow water edge habitat preferred by juvenile salmon. Instead, they would be open water or weed-choked and contain fairly high densities of predators such as striped bass or largemouth bass. The effect would be determined in large part by how easily it would be for juvenile salmon to be carried into the lagoons from the rivers and how easy it would be escape from them. High outflows down both rivers should minimize the effects of the lagoons, while low outflows should increase the likelihood that juvenile salmon would wind up in them, especially on the San Joaquin side of the Delta. It is possible that Suisun Marsh will be heavily used by juvenile salmon once it floods, because much of it will be productive shallow water habitat, if saline.

Effects on adult salmon would presumably be small because of their focus on swimming upstream through the Delta, although there would no doubt be some mortality if the breaches occurred during a period of significant migration.

Largemouth bass. Largemouth bass are introduced piscivores that have greatly expanded their populations in the Delta following the invasion of Brazilian waterweed. The waterweed provides habitat for the bass by creating cover for juvenile and adult bass, reducing flow rates through channels, and causing sediment to settle from the water, resulting in clearer water. It is only the most visible species of a complex of alien 'pond' species that thrive in waterweed dominated freshwater sloughs, including redear sunfish, bluegill, white catfish, black bullhead, and common carp. By and large these are the same species that are dominant in upstream reservoirs (Moyle 2002).

Largemouth bass and associated species would expand their populations further in flooded freshwater islands, once the Brazilian waterweed became established. While these species can survive in brackish water habitat, most of them avoid it and will probably be present in only low numbers in brackish lagoons without dense beds of waterweed.

*Marine fish***.** San Francisco Bay supports a diverse fauna of marine fishes that includes most of the common species found along the central California coast. The abundances of different species fluctuate both in response to ocean conditions and to freshwater flows into the Bay. Not surprisingly, some of the most abundant species are species that can tolerate moderately low salinities (euryhaline), such as Pacific herring, northern anchovy, staghorn sculpin, yellowfin goby, and starry flounder.   Juvenile of these forms frequently appear in the upper estuary, especially in Suisun Bay and Marsh, usually during periods of low river flows. Thus, the expanded brackish water habitat in the upper estuary is likely to increase habitat space for euryhaline marine species, especially during dry years.

*Overall fish responses***.** It should be evident from the above descriptions that responses of fish species to large-scale island flooding will be highly variable, a reflection of the complex habitat and the complex fish fauna. Unanticipated responses are also likely to the changed conditions. For example, inland silverside are now abundant in the shallow flooded areas of Sherman Island in the western Delta (W. A. Bennett, pers. comm.) and it is possible that it could colonize some of the newly flooded areas, depressing other fishes through predation and competition (Bennett and Moyle 1996). In addition, new alien invaders could cause major shifts in abundance of established species. For example, two piscivores are poised to invade the SFE: northern pike and white bass (Moyle 2002, Lund et al. 2007).   However, the general patterns of fish response to sudden large scale flooding would roughly be the following:

1. Fishes within the suction zone of Delta levee breaks (which could be a large area, given the capacity of the islands to accept large volumes of water) would be sucked into the island with some mortality from sediment in the water column, sudden changes in water quality (salinity, temperature, etc.), and other factors associated with the sudden

movement of large volumes of water. The species affected would depend on time of year of flooding and the location of the flooded islands.

2. Once the waters had settled down, there would be an initial period of low plankton densities, followed by blooms first of phytoplankton, then zooplankton, perhaps within a period of 1-3 months.

3. In the longer term (1-5 years), the new lagoons would assume the character of areas in the SFE with similar depths, flows, and salinities. Thus, those in the more eastern and central parts of the Delta would likely become dominated by Brazilian waterweed and a variable assemblage of alien freshwater fishes. Lagoons in the western Delta that maintained low (2-10 mg/l) salinities most of the time would have conditions similar to those in Suisun Bay. Planktonic productivity is greatly reduced in Suisun Bay by the filter-feeding overbite clam, but it still serves as an important rearing area for pelagic fishes, at least in some areas (Hobbs et al. 2006). These areas would provide expanded habitat for species such as striped bass, longfin smelt, and delta smelt, as well as additional feeding areas for sturgeon, splittail, and other benthic feeders that can consume clams and their associated faunas. A few lagoons that were created in intermediate locations, where salinities and other conditions would become highly variable among years and seasons because of the combination of river inflow and tidal exchange, could be highly productive systems that would support dense populations of plankton and planktivores, including delta smelt and striped bass. Such areas could become a source for enhanced populations of euryhaline fishes.

4. Over a longer term (5+ years), conditions in the lagoons would change further as levees continued wash away, parts of the lagoons filled in with sediment, and islands not flooded previously gave way to new hydraulic forces created by the lagoons (waves, changed current patterns, etc.), assuming most levees were not repaired. Essentially, much of the Central and South Delta could become one large embayment, similar to Suisun Bay, but fresher on its upper end. By size alone, this area would increase the amount of habitat for fishes. Presumably, the increased habitat would increase populations of some of the desirable open-water species although much of it would be dominated by waterweed and alien pond fishes or by relatively low productivity habitat dominated by overbite clam. In this period, Suisun Marsh would also have become at least partially flooded, with the potential for large increases in tidal brackish water habitat, favorable (depending on salinity regime) to desirable species such as longfin smelt, delta smelt, spittail, striped bass, and possibly juvenile Chinook salmon.

Thus the overall effect of massive flooding would likely to be to increase the populations of at least some desirable species while greatly increasing the abundances of less desirable aliens, such as largemouth bass and common carp. While there are fisheries for such species, they are deemed less desirable because the fish are non-native and have large populations outside the SFE, unlike the species deemed desirable.

Improving the estuary for fish

The above speculative discussion is based on the scenario that California will continue on its present track of managing the Delta environment through a combination of applying band-aid levee repairs, poorly regulating invasive species, removing large quantities of fresh water, managing Suisun Marsh as freshwater marsh, and monitoring desirable species as they decline. In short, the status quo consists of continuing business as usual until large-scale levee collapse forces large-scale action, much of it likely to be poorly planned and futile in the long run (Lund et al. 2007). As indicated above, the massive collapse of levees in the Delta and Suisun Marsh would not be a long-term disaster for fish and fisheries and could even be a slight benefit. The collapse could be a disaster for the California economy, however, mainly because it would disrupt the state's water supply system and other infrastructure (Lund et al. 2007). Thus a movement to actually 'fix' the Delta and Suisun Marsh before the inevitable disaster is highly desirable and several processes are underway at the state level to determine options. Lund et al. (2007) present nine scenarios for a future Delta and Suisun Marsh, five of which they regard as feasible. The four of the five protect water supply while allowing some portion of the Delta to remain as habitat for native fish and other desirable organisms. The five options provide suggestions for significantly improving the habitat in the Delta and Suisun Marsh for desirable species, provided action is taken before large-scale levee collapse occurs. The options of Lund et al. (2007) are only a tiny fraction of the hundreds of permutations and combinations of actions that could be taken; they are designed to represent examples of the reasonable alternatives possible to provide a visualization of management options.

Here I will not go through the alternatives but instead discuss actions that will allow fish-friendly habitat to develop while not necessarily reducing most of the services to humans that the SFE provides. These actions could be part of any scheme that seeks to modify the Delta to improve or protect its water supply functions as well its ecological functions. The general approach towards creating an environment in the SFE that is more friendly to desirable fish species (and other biota) presented here is to increase habitat heterogeneity. The basic concept is as follows: as much area as possible should support conditions resembling those of the historic SFE, especially in the Delta and Suisun Marsh, because these are the conditions to which the native fishes are adapted. However, the improved habitats are likely to be in different locations than they were historically because of changed elevations due to subsidence and sea level rise. Thus habitats once present in the deeply subsided center Delta will have to be located in the less-subsided peripheries.

A key part of a habitat creation program will be to have as much area as possible that fluctuates in salinity enough so freshwater and brackish water benthic invaders are discouraged while desirable (mainly native) pelagic species are favored. The exact extent, frequency, and range of salinity fluctuation needs to be determined by further studies of key organisms (both desirable and undesirable species), but present distributional limits of the organisms suggest that fluctuations required are likely to be in the range of 0 to 12 mg/l over 1-2 years, with high and low values sustained for 4-5 months at a time.

The following are some general, large-scale actions that could improve habitat heterogeneity and create areas with desirable conditions of water quality, including fluctuating salinity. This list is neither complete nor inclusive (Lund et al. 2007).

1. *Suisun Marsh.* This region of the SFE is headed inexorably to becoming brackish tidal marsh, unless huge amounts of money are spent on raising levees; such action may not even be possible as a permanent solution, given the compressibility of the marsh soils underlying the levees. Most of Suisun Marsh is currently intensely managed in diked sections, principally as freshwater habitat for waterfowl. Even under these conditions the intervening sloughs, especially in the few undiked areas, provide good,

often brackish, habitat for desirable fish (Matern et al. 2002, R. E. Schroeter, unpublished data). Improving the Marsh for fish will require systematically breaching or removing levees, initially in the areas most vulnerable to flooding and preferably after reconstruction of the original marsh drainage system and removal of infrastructure. Models for the creation of the new tidal (and subtidal) marsh areas can be found in the currently undiked section of marsh (Rush Ranch) that is part of the San Francisco Bay National Estuarine Research Reserve (http://rtc.sfsu.edu/nerr/sf_bay_reserve) and by an on-going experimental levee breach at Blacklock (http://www.iep.water.ca.gov/suisun/restoration). Even after radical restructuring of the Marsh, it may be desirable to continue to operate the large salinity control gates at the upstream end of the Montezuma Slough. This slough and Suisun Slough are the deep (2-6 m) main arteries of the Marsh and are the principal habitats of pelagic fishes such as delta smelt and longfin smelt, so it may be possible to operate the gates to increase the ranges of salinity that favor these species and discourage undesirable alien species.

2. *Cache Slough*. Cache Slough and adjoining areas make up essentially the northwest corner of the Delta. The region is of high restoration potential as tidal freshwater marsh and slough because (1) island subsidence is low compare to other parts of the Delta, (2) it maintains much of its original drainage pattern, even though most of the channels are leveed and artificial cross channels exist, (3) it is a major spawning and rearing region for delta smelt, (4) it has strong tidal currents that move water from the Sacramento River in and out of its channels, (5) it drains the lower end of the Yolo Bypass (next section), and (6) it contains the large recently (1998) flooded Liberty Island that is being used as an example of a "passive" restoration project (http://www.delta.dfg.ca.gov/jfmp/libertyisland.asp). The region can be relatively easily converted into an expanded version of the favorable tidal habitat for desirable fishes (as well as waterfowl and other biota) through levee breaches, elimination of cross channels, and other projects that improve circulation. It is also a region where it should be possible to create favorable habitats for delta smelt, mainly spawning beaches and productive rearing areas for larvae, that also discourage their egg and larval predators, especially inland silverside.

3. *Yolo Bypass*. To keep Sacramento from flooding, an artificial floodplain, the Yolo Bypass, was constructed in the 1930s. Essentially, when the Sacramento River reaches a certain stage of flow, it spills over two low barriers (Fremont Weir, Sacramento Weir) and into the 24,000 ha, 64 km long bypass (Sommer at al.2001a, b). The flood waters flow down the bypass and re-enter the Sacramento River via Cache Slough. The principal permanent water in the Yolo Bypass is the Toe Drain, which runs along the levee on eastern edge. About half the bypass is in the Delta; the Toe Drain in this region is essentially a leveed tidal slough, a branch of Cache Slough. The land in the bypass is a mixture of farmland and wildlife areas but when it floods it is high quality rearing habitat for Chinook salmon fry and splittail, as well as other fishes. The flood waters may also mobilize nutrients from the bypass, helping to support Delta food webs. From an ecological perspective, a problem with the Yolo Bypass is that is does not flood, even partially, every year. Construction of a gate on the Freemont Weir would permit limited controlled flooding from the Toe Drain every year, improving growth and survival of salmon and splittail and improving flows through Cache Slough to benefit delta smelt.

4. *San Joaquin floodplain.* The channel of the San Joaquin River above and through the Delta is highly channelized, and provides little favorable habitat for desirable fishes: the water tends to be deep and polluted in places (e.g., Stockton Ship Channel) and dominated by invasive aquatic plants and invertebrates in others. One way to improve the habitat for fish is to create one or more bypasses like the Yolo Bypass. This would involve removing or breaching levees from islands (e.g., Stewart Tract) that border the river to promote annual flooding. Such floodplain habitat is likely to be especially beneficial as rearing habitat for juvenile salmon coming from the San Joaquin River basin. An example of the benefits of restored floodplain in the Delta is provided by the small restored floodplain along the lower Cosumnes River, on the eastern fringe of the Delta, which has proved to be beneficial to several native fishes and provides experience in methods of modifying agricultural lands into fish-friendly floodplains (Moyle et al. 2007).

5. *Managed Delta islands.* The previous four actions have focused on areas at the edges of the upper estuary because of assumption that the subsided islands of the Delta will fill with water and together will become a large open-water system over which little control can be exerted, aside from regulating freshwater inflow under some conditions (Lund et al. 2007). However, with some foresight, it may be possible to retain the levee integrity of some islands, by making them into islands of regulated aquatic habitat. Essentially this concept follows the lead of Delta Wetlands, a private group that has sought to use Delta islands for water storage and wildlife habitat (http://www.deltawetlands.com/). The levees of habitat islands would be reinforced on the inside by having gradual slopes towards the interior, which would be planted with native vegetation to stabilize the soils. Gates on the upper and lower ends of the islands would be used to regulate water quality on the islands, including salinity. This concept would be especially useful for islands (e.g., Twitchell Island) in the western Delta located close the Sacramento River so that salinity could be manipulated by trapping either river or tidal water in the island as needed (as is currently done with tidal gates in Suisun Marsh). The islands of water could then be managed as nursery areas for desirable fishes. Ideally, the gates would also allow an island to be dried out completely on occasion to control undesirable alien species.

Invasive species

A major uncontrolled (for now) factor that can negatively affect efforts to create a more desirable, diverse (heterogeneous) ecosystem in the Delta is the invasion of new alien species that become agents of ecosystem change, such as the overbite clam or Brazilian waterweed have in the past. There is an identified queue of harmful invaders that are likely to arrive in the near future (Lund et al. 2007). Thus part of any program of ecosystem creation must include vigorous efforts to exclude new invaders from all sources, including the shipping, horticultural, pet, and aquaculture industries. There should also be in place a mechanism that allows quick action to eradicate a new invader before it spreads from the site of an invasion.

Conclusions

The San Francisco Estuary, especially the Delta and Suisun Marsh, is predicted to undergo drastic change in the next 50 years, with the probability of a major ‘disaster’ increasing through time, just on the basis of earthquakes and land subsidence alone

(Mount and and Twiss 2005). When sea level rise and increased frequency of flooding due to climate change are factored in, major change in this period seems inevitable. The disaster scenario, however, is mainly for human goods and services, especially water supply to urban and agricultural areas. From a fish perspective, the ecological changes resulting from flooding of numerous Delta islands and Suisun Marsh are likely to create conditions that should be at least as favorable for desirable species as present conditions, after a period of possible high mortality created by the initial flooding events. Potentially *more* favorable habitat will result from a disaster scenario simply because there will be increased area of open water and tidal marsh, some of it with enough fluctuation in salinity to be especially favorable to delta smelt, striped bass, and other pelagic species now in decline. There is much uncertainty, however, about how much favorable habitat will be created under disaster scenarios because of the tendency of alien invaders to quickly dominate so many habitats. Thus, making efforts to control the way the habitat changes, as suggested above and in Lund et al. (2007), could have major benefits while being highly compatible with changing the ways in which services the Delta provides are delivered, especially water supply. The principal basis for action is to increase habitat heterogeneity over present and likely future conditions, as well as to increase the total amount of aquatic habitat. No matter what actions are taken there will be a high degree of uncertainty in the ecological benefits but the present situation in the estuary represents an unprecedented opportunity to reverse the impacts of over 150 years of negative ecological change.

Acknowledgements

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Literature Cited

Bay Institute. 1998. From the Sierra to the sea: The ecological history of the San Francisco Bay-Delta Watershed. Bay Institute of San Francisco, Novato CA. http://www.bay.org/sierra_to_the_sea.htm.

Bennett, W. A. 2005. Critical assessment of the delta smelt population in the San Francisco Estuary, California," San Francisco Estuary and Watershed Science [online serial] 3 (2): 1-71. *http://repositories.cdlib.org/jmie/sfews/vol3/iss2/art1*.

Bennett, W.A., and P. B. Moyle. 1996. Where have all the fishes gone: interactive factors producing fish declines in the Sacramento-San Joaquin estuary. Pages 519-542 *in* J. T. Hollibaugh, ed. San Francisco Bay: the Ecosystem. San Francisco: AAAS, Pacific Division.

Brandes, P. L. and J. S. McClain. 2001. Juvenile Chinook salmon abundance, distribution, and survival in the Sacramento-San Joaquin Estuary. Pages 39-137 *in* R. L. Brown, ed. Contributions to the biology of Central Valley salmonids, California Department of Fish and Game Fish Bulletin 179, Vol. 2.

Cohen, A. N., and J. T. Carlton 1998. Accelerating invasion rate in a highly invaded estuary. Science 279: 555-557.

Department of Water Resources. 1993. Sacramento-San Joaquin Delta Atlas. Sacramento, CA. California Department of Water Resources.

Department of Water Resources 2007 [Draft of Delta Risk Management Strategy Report, publically available by time this paper is published].

Dettinger, M. D. 2005. From climate-change spaghetti to climate-change distributions for 21st century California. San Francisco Estuary and Watershed Science [online serial] 3(4): *http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4*.

Herbold, B., A. D. Jassby, and P. B. Moyle. 1992. Status and trends report on aquatic resources in the San Francisco Estuary. San Francisco Estuary Project. 257 pp.

Hobbs, J. A., W. A. Bennett, and J. E. Burton. 2006. Assessing nursery habitat quality for native smelts (Osmeridae) in the low-salinity zone of the San Franscisco Estuary. Journal of Fish Biology 69:907-922.

Hobbs, J. A., W. A. Bennett, J. Burton, and M. Gras. 2007. Classification of larval and adult delta smelt to nursery areas by use of trace elemental fingerprinting. Transactions, American Fisheries Society 136:518-527.

Hollibaugh, J. T. ed.1996. San Francisco Bay: the ecosystem. San Francisco: AAAS, Pacific Division.

Light, T. and M.P. Marchetti. 2007. Distinguishing between invasions and habitat changes as drivers of diversity loss among California's freshwater fishes. Conservation Biology 21:434-446.

Little Hoover Commission. 2005. Still imperiled, still important. The Little Hoover Commission's review of the CALFED Bay-Delta Program. Sacramento, California.

Lund, J., E. Hanak., W. Fleenor, R. Howitt, J. Mount, and P. Moyle. 2007. Envisioning futures for the Sacramento-San Joaquin Delta. San Francisco: Public Policy Institute of California. 284 pp.

Matern, S. A., P. B. Moyle, and L. C. Pierce. 2002. Native and alien fishes in a California estuarine marsh: twenty-one years of changing assemblages. Transactions of the American Fisheries Society 131:797-816.

Moyle, P. B. 2002. *Inland Fishes of California. Revised and expanded*. Berkeley: University of California Press. 502 pp.

Moyle, P.B., R. D. Baxter, T. Sommer, T. C. Foin, and S. A. Matern. 2004. Biology and population dynamics of Sacramento Splittail (*Pogonichthys macrolepidotus)* in the San Francisco Estuary: a review. San Francisco Estuary and Watershed Science [online serial] 2(2):1-47. *http://repositories.cdlib.org/jmie/sfews/*

Moyle P.B., Crain P.K., and Whitener K. 2007. Patterns in the use of a restored California floodplain by native and alien fishes. San Francisco Estuary and Watershed Science .*http://repositories.cdlib.org/jmie/sfews/*

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

Nobriga, M. L., F. Feyrer, R. D. Baxter, and M. Chothowski. 2005. Fish community ecology in an altered river delta: spatial patterns in species composition, life history strategies, and biomass. Estuaries 28: 776-785.

Sommer, T. R., W. C. Harrell, M. Nobriga, R. Brown, P. B. Moyle, W. J. Kimmerer and L. Schemel. 2001a. California's Yolo Bypass: evidence that flood control can be compatible with fish, wetlands, wildlife and agriculture. Fisheries 58(2):325-333.

Sommer, T. R., M. L. Nobriga, W. C. Harrell, W. Batham, and W. J. Kimmerer. 2001b. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Sciences 58: 325-333.

Williams, J. G. 2006. Central Valley salmon: a perspective on chinook and steelhead in the Central Valley of California. San Francisco Estuary and Watershed Science 4 (3) Article 2. *http://repositories.cdlib.org/jmie/sfews/vol4/iss3/art2*

Supplementary testimony for the hearing held by The Subcommittee on Water and Power, Committee on Natural Resources, "Extinction if not sustainable water policy: the Bay-Delta crisis and the implications for California water management." Vallejo, CA. July 2, 2007

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1. In their testimony before the Subcommittee, Mr Steve Thompson (US Fish and Wildlife Service) and Mr. L. Ryan Broddrick (California Department of Fish and Game) indicated that their agencies had done everything in their power to protect the delta smelt, through adaptive management and other means. I respectfully disagree. As I indicated in my verbal testimony, most steps taken to protect the smelt were made only to minimize damage to the population rather than to actually improve conditions (as would seem to be necessary for recovery). Even actions to limit damage seemed to currently be in abeyance given the extremely low numbers of smelt taken in sampling programs and the numbers of smelt taken by the state and federal export pumps. As the result of increasing export of water from the SWP pumps at Tracy, in the two days before the hearing 390 and 258 smelt (data presented by Mr. Johns at the hearing), respectively, were entrained (killed) at the pumps. On the day of the hearing, 311 delta smelt were entrained. Since May 10 of this year nearly 2500 delta smelt have been taken at the pumps. Numbers are certainly higher because only smelt greater than 20 mm long are counted. Actions that could have been taken to protect the smelt this year, but were largely *not* performed were recommended in two letters by myself and Dr. Christina Swanson that were sent to the five agencies directly involved with smelt management on March 14 and June 1, 2007. These recommendations were not original with us but stemmed from recommendations by the agencies' own biologists.

2. Mr. Thompson and Mr. Broderick indicated that changing the status of the delta smelt from Threatened to Endangered, as requested in an emergency petition filed over a year ago (March 8, 2006), would not have affected management of the species. Again, I respectfully disagree. Endangered listing would be dramatic acknowledgement of the critical state of the smelt population, with the potential to mobilize additional resources for protection of the smelt, as well as public support for actions taken. If the smelt was listed as endangered under the federal Endangered Species Act, it is highly likely that the continued mortality of smelt at the SWP pumps not would be allowed to continue.

3. Mr. B. J. Miller presented testimony in which he stated that there is no linear relationship between the amount of exports and delta smelt numbers. He further stated that because of the lack of a relationship, agency and other biologists never show graphs relating exports to smelt numbers even though they claim a relationship exists (i.e., are in denial about the lack of a relationship). There is evidence to the contrary. Attached to this submittal is a graph showing a negative relationship between exports and smelt numbers that was part of the emergency listing petition submitted in 2006. The relationship is weak but present. In any case, a direct relationship is not needed to show

that the pumps in the south Delta can impact smelt populations. In a recently published, peer-reviewed paper (unlike Mr. Miller's analysis), Dr. William Bennett has provided some strong indications that the increase in early season pumping has impacted smelt because it kills the biggest, most fecund smelt (and probably their offspring), which contribute the most to future generations. This is the "big mama" hypothesis mentioned at the hearing. Exports from the Delta are clearly not the only cause of smelt decline but there is every reason to thing they are an important contributing factor, especially when populations are as low as they are today.

4. It is not at all certain that the delta smelt will make it though another year. If it does survive, it will be again in record low numbers. This crisis emphasizes the need not only to take actions to improve conditions for delta smelt as much as possible but to start taking large-scale actions to make sure smelt habitat is present in the future, as suggested in the UCD-PPIC report and indicated in my previous written testimony.

From: Emergency petition to list the delta smelt *(Hypomesus transpacificus)* as an endangered species under the endangered species act, submitted to the U. S. Fish and Wildlife Service by the Center for Biological Diversity, The Bay Institute, and the Natural Resources Defense Council, March 8, 2006

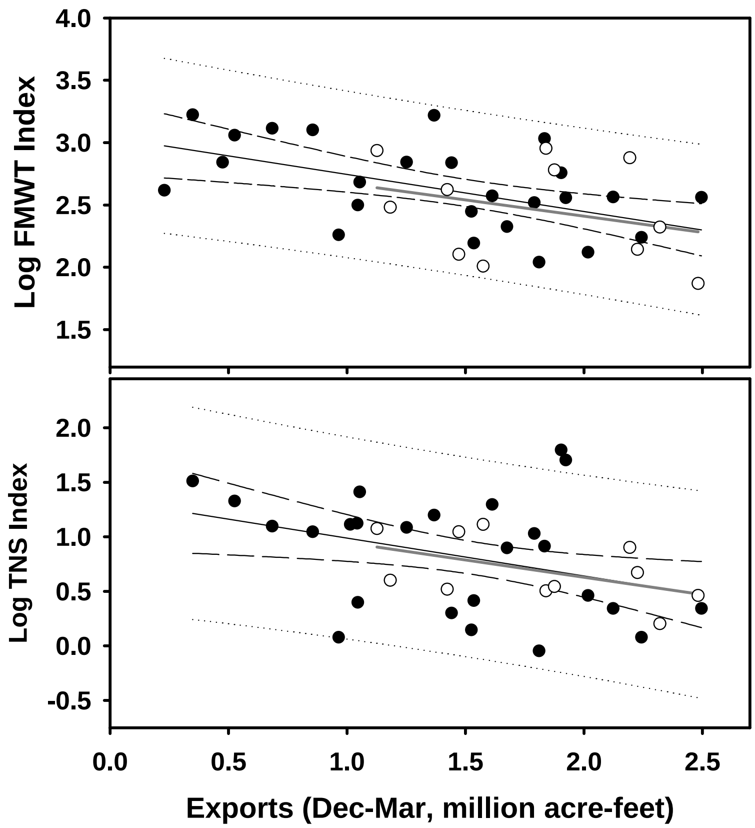

Figure 6. The relationship between winter (December-March) export amounts and subsequent abundance of delta smelt. a) sub-adult and adult delta smelt as measured by the FMWT Index (using data from 1967-2004); and b) juvenile delta smelt as measured by the TNS Index (using data from 1969-2004). For each graph, the regression, 95% confidence limits and the prediction limits are shown calculated for the entire datasets. The open symbols and the dark gray regression line highlight the years since the delta smelt was listed under the ESA (1994-2004). Data Sources: California Department of Fish and Game, California Department of Water Resources, Dayflow.

Large scale ecological changes have occurred in the Delta during the past 30 years, such as the establishment of the invasive clam *Corbula amurensis* and its impacts on the planktonic food web, but they do not strongly affect the results of these types of correlation and regression analyses. For example, the significant relationship between winter exports and the subsequent population abundance of adult delta smelt was apparent in the 20 years prior to the clam's invasion (1967-1985, Equation 5).

Adult delta smelt (1967-1986):

Log FMWT = 3.109 – 0.353(Dec-Mar exports, MAF) **(Equation 5)**

$n=18$; $p=0.013$; $r^2=0.0329$, $SEE=0.308$

Linear regression using smaller subsets of more recent years (e.g., post-*Corbula* invasion, 1987-2004 or 2005; post-ESA listing, 1994-2004 or 2005) were not statistically significant but both the slopes and intercepts of the relationships were very similar to those generated using the entire dataset (e.g., 1994-2004(5): open symbols and grey regression line in Figure 6). The significant relationship between winter exports and abundance was not "driven" by the low abundances measured during the past three or four years. For example, after excluding the three most recent years for the FMWT abundance indices (2002-2004) from the dataset, the regression was still significant ($p=0.02$) and the slope and intercept were similar to those generated with the entire dataset. Given that the significant relationship between winter exports and adult abundance was detectable by 2002 (and before), this indicates that the low abundances measured during the past three years, a period during which winter exports were at near record high levels, were predictable as early as three years ago.

The abundance of juvenile delta smelt was also significantly affected by spring-summer exports (March-July). The linear regression for this relationship is:

$$\text{Log TNS} = 1.429 - 0.369(\text{Mar-July exports, MAF}) \qquad \textbf{(Equation 6)}$$

$N=36$; $p=0.047$; $r^2=0.111$; $SEE=0.462$

In 1993, the USFWS (1993) identified 21 major federal, state, local or private organization proposals for increased exports. Since that time, Delta water exports and corresponding impacts on delta smelt have increased and they are projected to continue to increase in the future. The recent 5-year review (USFWS 2004b) noted that the potential threat of increased demands on surface water resources in the Central Valley and Delta was growing, citing planned or proposed new water diversion projects such as the Freeport Regional Water Project, increases in pumping capacity at the SWP pumping plant as part of the South Delta Improvement Project, the California Aqueduct/Delta-Mendota Canal inter-tie to allow increased pumping at the CVP pumping plant, Empire Tract on the San Joaquin River; and potential expanded water storage capacity projects at Los Vaqueros, north of the Delta off-stream storage, Shasta Reservoir, in-Delta storage, and south of the Delta surface and groundwater storage projects. The USFWS (2004b) concluded that the increased storage and diversion capacity would likely result in lower freshwater outflows to the estuary, higher water exports from the Delta, and greater entrainment of delta smelt.