SAN FRANCISCO BAY SUBTIDAL HABITAT GOALS REPORT

Appendix 1-3: Anthropogenic Impacts on San Francisco Bay and its Subtidal Habitat

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ANTHROPOGENIC IMPACTS ON SAN FRANCISCO BAY AND ITS SUBTIDAL HABITAT

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Between 1849 and the present, San Francisco Bay went from pristine conditions to being a strong contender for the titles of "most modified" (Nichols et al. 1986) and "most invaded" (Cohen and Carlton 1998) estuary in the nation. Although records of pre-disturbance conditions are scanty, we know that native birds, fish, shellfish, and plants in great abundance flourished in Bay waters and in the vast tidal marshes that ringed the subtidal area.

In the century and a half following the Gold Rush, human activities caused rapid and dramatic alterations to the Bay. Gold-mining left a legacy of mercury-laden mining debris in Bay sediments. A number of fish and shellfish species were briefly exploited, until each fishery collapsed. The Bay's bathymetry was altered as ship channels were dredged and bridges were built. Most of the surrounding wetlands were either diked and drained for agriculture or salt production, or filled for urban development, including as part of shoreline erosion protection measures like riprap. A vast system of dams and diversions, created to redirect water to agriculture and urban areas, changed both the quantity and timing of freshwater inputs to the Bay. Pesticides and other pollutants were carried into the Bay by runoff from urban and agricultural areas. And large numbers of exotic species from around the world were brought in by various transport mechanisms and became established.

These and other transformative activities and events are described in this chapter. While each activity has its own unique history, a common theme is that in nearly every case effects on the Bay—and particularly effects on the subtidal area—were unsuspected or ignored until fairly recently. But in the last few decades, growing awareness and concern about anthropogenic impacts on the Bay ecosystem, and new environmental laws and regulations at all levels of government, have affected virtually every activity that impinges on the Bay.

Relevance of history to Subtidal Habitat Goals Project

As discussed throughout this report, the target for the Subtidal Habitat Goals Project is defined as net improvement of ecosystem function, taking current conditions as the baseline. Even though the goals are not intended to turn back the clock and re-create the conditions of an earlier time, knowledge about historical conditions and past human activities is critical to formulating realistic, achievable goals for the subtidal system:

- Knowledge about pre-disturbance conditions informs our vision of what is possible shapes our understanding of what improvement might look like, and may provide clues about specific conditions that are conducive to increasing the abundance of native species.

- Knowledge about the mechanisms of historical changes provides insights about how undesirable changes might be halted, reduced, remedied, or reversed.
- Knowledge about the nature of the changes, especially the degree to which they are reversible, helps identify opportunities for improvement/restoration as well as constraints.

DIKING, FILLING, SHORELINE HARDENING, AND ARTIFICIAL STRUCTURES

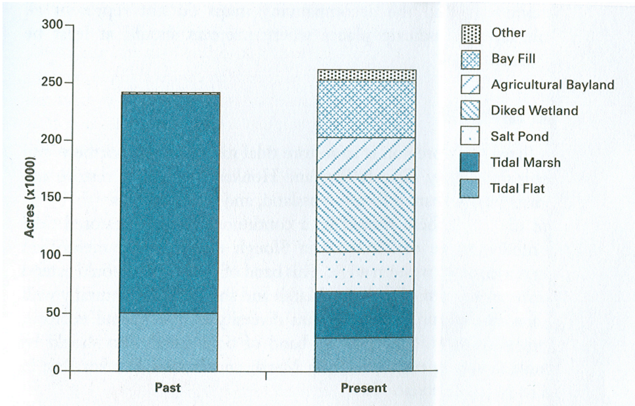
Since 1848, human activities have dramatically decreased the area of tidal wetlands surrounding San Francisco Bay and Delta. These losses have come about through (1) filling; (2) diking and draining, usually for agriculture or livestock grazing; and (3) diking to create salt ponds, managed marsh, or other diked wetlands. The different activities have occurred to different extents in different regions of the Bay. Filling is the most irreversible, especially when (as has usually been the case) the filled area is developed.

San Francisco Bay has been especially vulnerable to diking and filling, both because much of it is shallow (at low tide about two thirds of the Bay is less than 18 feet deep), and because ownership of the Bay is divided among multiple entities both governmental (state, federal, counties, and cities) and private (Wilmar 1982).

Diking and filling slowed dramatically after the Bay Conservation and Development Commission's San Francisco Bay Plan was adopted by the California legislature in 1969, but by that time the great majority of the historic tidal wetlands had been filled or converted to other wetland types (Monroe and Kelly 1992).

Figure 1 illustrates the historic and current extent of various types of Baylands habitat in San Francisco Bay (Goals Project 1999). (Baylands are defined in Goals Project 1999 as "the lands that lie between the elevations of the high and low tides, including those areas that would be covered by the tides in the absence of levees or other structures.")

Figure 1. Past and Present Baylands Habitat Acreage



Source: Goals Project 1999 [This is part of Figure 5.1]

Fill

A total of 50,000 acres of San Francisco Bay Baylands have been filled (Goals Project 1999). This figure includes former shallow-water areas that were filled (Robin Grossinger, pers. comm.). The places with the most fill are the urban areas bordering the Central Bay and northern portions of the South Bay (especially San Francisco, the East Bay cities, and Silicon Valley) (Figure 2). Most of the fill is developed (about 43,600 acres, as compared to about 7,600 acres of undeveloped fill) (Goals Project 1999).

Figure 2. Areas filled by 1998

Source: Goals Project 1999 [from Figure 2.8]

Caption: About 50,000 acres of the Bay have been filled.

Diked wetlands and salt ponds

Historically several areas around San Francisco Bay were diked and drained for agriculture or pasture, especially around Suisun Bay and North Bay. However, because of problems with salinity some of these areas were subsequently converted into managed brackish-water wetlands, especially in Suisun Bay (see below). Today about 1,500 diked acres around Suisun Bay and about 28,000 around the North Bay are in agricultural use (see Figure 1, "agricultural Bayland") (Goals Project 1999).

About 65,000 acres around San Francisco Bay consist of diked wetland, about 80 percent of which is managed for wildlife, primarily waterfowl, in private duck clubs and publicly owned refuges. Suisun Marsh is by far the largest such area (Goals Project 1999).

Historically there were some natural salt ponds along the eastern edge of the South Bay that were used by Native Americans, but none of these remain today. Diking of tidal flats and marshes for commercial salt production began around 1860 in the South Bay and was extended to the North Bay in 1952. By the mid-1950s, almost half of the historic tidal marsh area in the South Bay and almost one-fifth in the North Bay had been converted to commercial salt ponds. The North Bay salt ponds are now inactive and managed for wildlife. As of 1998, there were about 34,000 acres of active and inactive salt ponds (Goals Project 1999).

Figure 2. Areas diked by 1998

Source: Goals Project 1999 [from Figure 2.8]

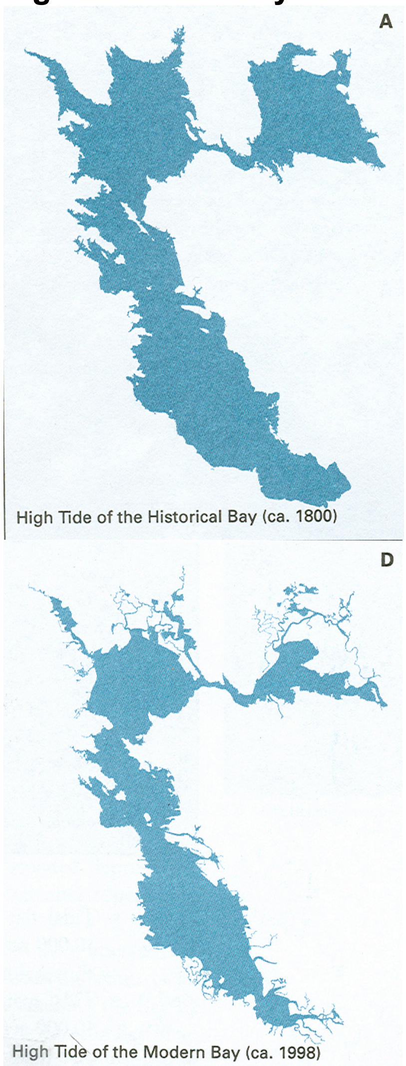
Caption: About 139,000 acres of the Bay were diked by 1998.

Loss of Subtidal habitat

While the reductions in the overall area of the Bay are dramatic (Figure 3), most of these losses occurred in the intertidal zone. The subtidal area of the Bay has changed much less. According to the Goals Project 1999 report, the area of shallow (up to 18 feet below mean lower low water, MLLW) Bay and channel habitat has decreased only about 1.5% (from 174,000 to 172,000 acres), an amount which is likely within the uncertainty of the measurements (Robin Grossinger, pers. comm.). Deep (> 18 feet below MLLW) Bay and channel habitat has decreased about 17%, from 100,000 to 82,000 acres (Goals Project 1999). The reductions have been caused partly by fill (in shallow areas) and partly by sedimentation from various causes, including hydraulic mining debris.

Loss of subtidal habitat has been greatest in Suisun and San Pablo Bays (Goals Project 1999).

Figure 3. Summary of losses from diking and filling



Source: Goals Project 1999 [from Figure 2.8]
Historically, the total area of the Bay at high tide was about 516,000 acres. Now the total area of the Bay at high tide is about 327,000 acres.

Delta

Although most of the Delta is outside the geographic scope of the Subtidal Habitat Goals Project, wetland loss in the Delta is relevant because of its impacts on subtidal habitat.

Land reclamation in the Delta began almost simultaneously with the Gold Rush as the new settlers quickly recognized the farming potential of the rich peat soil and silt. The pace of reclamation increased dramatically with technological advances like the steam-power dredge, first used in the 1870s (Bay Institute 1998). By the mid-1930s the conversion of the Delta into a system of reclaimed islands separated by channels was essentially complete (Lund *et al*. 2007).

The conversion of Delta marshlands to farmland represents the greatest wetland loss in the greater Bay-Delta estuary. Historically the Delta was the largest tidal marsh in the Bay-Delta system, covering 345,000 acres. Today the Delta contains only about 8,000 acres of tidal marsh (Monroe and Kelly 1992). For comparison, San Francisco Bay downstream of the Delta historically contained 190,000 acres of tidal marsh and currently contains 40,000 (Goals Project 1999).

SHORELINE HARDENING AND ARTIFICIAL STRUCTURES

Humans have also altered the estuary's shoreline by installing ports, docks, marinas, bridges, levees, seawalls, and other hard structures—particularly riprapped revetments—along and near its edges. While not a lot of information on the potential impacts of these structures to the estuary's flora and fauna, it is known that these structures can alter both littoral drift and redirect erosive forces (BCDC 1988). Besides displacing Bay volume and reducing water surface area, erosion control structures often impact nonvegetated, intertidal areas (usually mudflats), with important habitat values. They tend to eliminate the transition zone between uplands and tidelands, and plants and animals other than what were there before colonize the structures, which could possibly have an indirect impact on subtidal areas. Between 1978 and 1987, approximately 41 acres were filled in the Bay as part of permitted shoreline erosion projects. Most of this fill was for a few large projects (BCDC 1988). Some of those projects extend into subtidal areas (BCDC 1988). While artificial structures can eliminate, shade out, or otherwise harm eelgrass and other subtidal habitat, they also offer roosting places for birds (see Cohen 2008, Appendix 2-1). One example is a colony of California Least Terns that uses the detached breakwater off the former Alameda Naval Air Station.

And particularly in parts of the Bay where natural substrates are rare (most of the Bay outside of the western Central Bay), artificial substrates may provide settlement opportunities for exotic organisms, facilitating their spread and increasing their abundance within the Bay (see Cohen 2008, Appendix 2-1). Artificial structures can also change the bottom of the Bay. Bay mussels, including both a native (*Mytilus trossulus*) and an exotic species (*M. galloprovincialis*) and/or hybrids between them, are common or abundant on many of the structures in the Bay. Over time, the accumulation of dead shells from these structures can change the adjacent bottom type to shell hash (see Cohen 2008, Appendix 2-1).

POLLUTION

Silt and Mercury From Historic Mining

The first human event to cause major impacts to San Francisco Bay actually took place quite far from the Bay itself. This event was the Gold Rush, set off by the 1848 discovery of gold in the Sierra foothills about 100 miles northeast of San Francisco.

By 1853, mining companies were using hydraulic mining techniques in which giant "water cannons" aimed huge jets of water, under pressures of hundreds of pounds per square inch, at gold-bearing riverbanks and hillsides. The material washed away was directed into sluices hundreds to thousands of feet long, which were lined with elemental mercury (quicksilver) to capture the gold by amalgamation (Hunerlach et al. 1999). Tens of millions of cubic meters of hydraulic mining debris, consisting of rock, gravel, sand, and mud, were annually washed into Sierra streams and carried into Central Valley rivers, causing disastrous floods (Nichols et al. 1986).

After years of lawsuits by Central Valley farmers and towns, hydraulic mining was effectively ended in 1884 when Judge Lorenzo Sawyer of the federal Ninth Circuit court in San Francisco granted an injunction making it illegal to discharge mining tailings into streams and rivers (Kelley 1959). The effects of hydraulic mining on San Francisco Bay did not factor into the Sawyer decision and were not recognized until later. However, these effects were significant.

Sediment deposition

In recent studies, researchers have used surface-modeling software to conduct very detailed analyses of historical hydrographic surveys whose dates bracket the approximate period of hydraulic mining activity. These analyses have determined that approximately 115 million cubic meters of sediment, mostly hydraulic mining debris, were deposited in Suisun Bay (including Carquinez Strait) between 1867 and 1887 (Cappiella et al. 1999) and approximately 270 million cubic meters were deposited in San Pablo Bay between 1856 and 1887 (Jaffe et al. 2007). Gilbert's analysis, published nearly a century ago, of the same surveys yielded quite similar estimates for those embayments, as well as an estimate of 190 million cubic yards (about 150 million cubic meters) of hydraulic mining debris deposited in other parts of the Bay between 1856 and 1896 (Gilbert 1917).

The deposited silt from hydraulic gold mining caused dramatic hydrologic changes, including a temporary doubling of tidal flats in San Pablo Bay between pre-hydraulic mining times and 1887 (Jaffe et al. 2007). According to Nichols et al. (1986), silt from hydraulic mining contributed to a permanent reduction in open-water areas of the Bay. Today most of the hydraulic mining debris deposited in Suisun Bay has been washed further down-estuary, but probably about 200 million cubic meters remain in the northern part of the Bay, mainly in San Pablo Bay (Jaffe et al. 2007; B. Jaffe, pers. comm.). For more on sediment, see Cohen, Appendix 2-1, and Climate Change section below.

Mercury
A more lasting and damaging legacy of historic mining is mercury contamination. Currently San Francisco Bay is listed under Clean Water Act Section 303(d) as impaired for mercury contamination, and many Bay-caught sport fish exceed the EPA human health criterion of 0.3 mg methylmercury/kg fish tissue (Johnson and Looker 2004).

A great deal of the mercury used by gold miners to amalgamate gold was lost to the environment. Some of this mercury remains in Central Valley watersheds and continues to be carried to the Bay by the Sacramento and San Joaquin Rivers, but most was transported to the Bay during the mining era and now lies buried in sediments in Suisun and San Pablo Bays. Hornberger et al. (1999) estimate that as much as 10,000 metric tons of mercury from hydraulic mining could have entered the Bay, while other reports (Bay Institute 1998, Monroe and Kelley 1992, Wiener et al. 2003, Jay et al. 2003) suggest amounts more in the range of 2,500 to 5,000 metric tons.

Mercury mines were, and are, another major source of contamination. Most of the mercury used by gold miners in the Sierra came from mines located throughout the Coast Range, the largest being the New Almaden mine near San Jose, in the Guadalupe River watershed.

According to a San Francisco Regional Water Board staff report (Johnson and Looker 2004) prepared in support of a proposed mercury TMDL for the Bay, the largest single source of mercury to Bay waters is bed erosion in San Pablo Bay and Suisun Bay. Bed erosion brings buried mercury-laden sediments into the active sediment layer (i.e., the layer that is regularly resuspended and deposited, or the top 15 cm). The next three major sources, in descending order, are runoff from the Central Valley, urban stormwater runoff, and ongoing contamination from historic mercury mines and downstream mercury deposits in the Guadalupe River watershed. The total contribution to the Bay from these and other sources is estimated at 1,220 kg mercury per year (long-term average).

Current inputs of mercury from all sources are dwarfed by the quantity of legacy mercury in sediments, which is greater by a couple of orders of magnitude. Johnson and Looker (2004) estimate the current mass of mercury in the top 15 cm of sediment as 63 metric tons. A ballpark figure for the total amount of mercury in Bay sediments, including deep sediments, is about 200 metric tons (B. Jaffe, pers. comm.).

Mercury is present in the Bay in multiple chemical forms. One form—methylmercury—is of particular concern, even though it is typically only about one percent of total mercury. Methylmercury biomagnifies in the food web, and is a neurotoxin that is especially harmful to early stages of human and animal development (see Cohen 2008, Appendix 2-1).

Methylmercury concentrations often change substantially over short distances and short times, and do not correlate closely with concentrations of total mercury. The factors that control methylmercury concentrations in the Bay are not well understood. Since wetlands appear to be sites of methylmercury production, the ongoing restoration of Bay wetlands is of concern to some scientists. On the other hand, some recent studies suggest that some wetlands can trap methylmercury and render it unavailable for biotic uptake (see Cohen 2008, Appendix 2-1).

Several studies have found elevated levels of mercury in Bay biota, including the endangered California clapper rail. Most of the mercury in the Bay is bound to sediment particles and is distributed so widely in the Bay and its watershed that it will take many decades for the Bay's total mercury concentrations to decline significantly. Any more rapid improvement in the status of mercury in the Bay will depend on identifying and implementing effective management actions to control methylmercury (see Cohen 2008, Appendix 2-1).

Other Pollutants

In addition to mercury, the estuary is contaminated with several other long-lived pollutants, plus new and emerging ones.

Although serious pollution of Bay and estuary waters began in the 1850s, as a result of mining activities, by the late 1800s, oils spills and discharges and untreated domestic sewage were also affecting water quality (NOAA 2007). Then, in the early to mid-1900s, increasing amounts of industrial, agricultural, and automotive wastes began to enter the Bay (Monroe and Kelly 1992). Efforts to control these pollutants began after the public complained about foul smells and raw sewage floating in the Bay. The untreated sewage contributed to the decline of fish and shellfish populations, and anaerobic conditions were fairly common, particularly near sewage outfalls along the east and south shorelines of the Bay (The Bay Institute 1998). Municipal wastewater plants began primary treatment of sewage (disinfection and solids removal) in the 1950s, followed by secondary treatment (biological breakdown of organics) in the 1960s, and then by tertiary treatment (which targeted persistent pollutants or treated the effluent for re-use) as well as pretreatment programs to reduce industrial wastes discharged into municipal systems, in the 1970s. Outfalls were moved to deeper water to dilute and disperse the discharges (NOAA 2007). This improved wastewater treatment has resulted in better oxygen content in the Bay (San Francisco Estuary Project 2006).

Today there are 47 municipal and 15 major industrial plants discharging trace metals and other contaminants into the Bay and Delta (SFWQCB 2007). Urban runoff carries metals, PAHs, PCBs, and pesticides into the Bay and Delta via stormwater and dry season flows, as well as floatable debris—mainly plastic and polystyrene pellets—that can end up being ingested by wildlife or entangling them. Both urban and agricultural runoff carries pesticides and herbicides, nitrates, phosphates (applied as fertilizer), and selenium leached from soils in the Central Valley. Oil and petroleum continue to enter the Bay from accidental spills and leaks from boat and ship engines; oil, grease, and antifreeze are also washed into storm drains from leaking car and truck engines, street-side oil changes, and other human activities. Leachate from landfills, chemical spills, and herbicides used to control invasive aquatic species can also end up in the Bay, as can contaminants like dioxins that settle out from the air (Monroe and Kelly 1992; Cohen 2000).

While contamination due to many toxic chemicals has generally been declining since the 1950s and 1960s, long-term trends for pollutants of current concern vary from pollutant to pollutant. Mercury concentrations in striped bass have shown little change in thirty years while mercury concentrations in clapper rail eggs have been shown to be high enough to cause embryo mortality (San Francisco Estuary Project 2006). PCB concentrations appear to be gradually declining, but have been shown to still be high enough to cause low rates of bird embryo mortality and to affect immune response in harbor seals. Selenium concentrations appear to be high enough to cause abnormalities in the early life stages of Sacramento splittail and white sturgeon. Concentrations of DDT, chlordane, and other legacy pesticides have declined more rapidly and may soon generally be below levels of concern.

Concentrations of chemicals in current use, such as pyrethroid insecticides and polybrominated diphenyl ethers (PBDEs) are on the increase (San Francisco Estuary Project 2006). Concentrations of PBDEs have risen in both water and soil on the Bay bottom over the last several years (San Francisco Estuary Institute 2007). Levels of PBDEs in harbor seals have been rising for the past decade. Although two forms of PBDEs were banned by the state legislature (the bans take effect in 2008), a third form is still widely used in electronic production and hasn’t been banned. Some pyrethroids, used in lawn products, outdoor sprays, and on crops, have been shown in laboratory studies to kill the small crustaceans eaten by fish and amphibians; the state Department of Pesticide Regulation is reviewing studies of pyrethrins to try to assess their safety. San Francisco Estuary Institute’s Pulse of the Estuary 2007 names pyrethroids, toxins from blue-green algae, effects of the state and federal water projects (see Freshwater Diversions), and invasive species as possible culprits in the decline of four Bay fish species: striped bass, longfin smelt, threadfin shad, and Delta smelt. See Cohen 2008, Appendix 2-1, for more on emerging contaminants.

EXOTIC SPECIES

Every habitat in San Francisco Bay, except possibly the deep floor of the Central Bay, has been invaded by exotic species, and in some regions 100 percent of the common species are introduced (Cohen and Carlton 1995). Exotics can outcompete native species, displace them, and/or alter their habitat. Cohen and Carlton (1998) reported 234 species in the Bay-Delta estuary that are known to be exotic; the number as of 2007 is probably over 275 (A. Cohen, pers. comm.). The majority of these are invertebrates (about 70 percent). Nearly 15 percent are fish, about 12 percent are plants, and 4 percent are protozoans (Cohen and Carlton 1995).

Table: Discovery Year and Introduction Route for Selected Exotic Species in the Bay

Species	Discovered	Probable route of introduction	Comments
Balanus improvisus (Atlantic barnacle; Bay barnacle)	1853	Ship fouling	First record of an introduced species in Bay
Alosa sapidissima (American shad)	1871	Intentional	First fish successfully introduced in California. Commercial harvest in upper Bay and Delta 1874-1957; now sportfishing.
Mya arenaria (soft-shell clam)	1874	Atlantic oyster shipments	Historic commercial harvest (peaked 1890s); noncommercial harvest now
Morone saxatilis (striped bass)	1879	Intentional	Commercial fishery 1889-1935; now principal sport fish caught in Bay
Urosalpinx cinerea (oyster drill)	1890	Atlantic oyster shipments	
Teredo navalis (Atlantic shipworm, naval shipworm)	1913	Ship fouling	Caused major damage to wooden structures in northern Bay, 1919-1921
Corbicula fluminea (Asian clam)	1945	Uncertain; probably imported for food	Mainly a freshwater species; dominant mollusk in Delta; sometimes found in Suisun Bay
Venerupis philippinarum (Japanese littleneck clam)	1946	Japanese oyster shipments	
Spartina alterniflora (smooth cordgrass)	1970-73	Intentional (marsh restoration)	Hybridizes with and displaces native *Spartina foliosa*; alters salt marshes; may indirectly harm some marsh-nesting birds
Corbula amurensis (overbite clam; Asian clam; Amur River clam)	1986	Ship ballast water	Within one year of discovery became most abundant benthic organism in northern part of Bay
Eriocheir sinensis (Chinese mitten crab)	1992	Ship ballast water or intentional release	

Information in table mainly from Cohen and Carlton 1995

Routes of introduction

The first major route of exotic species introduction to the Bay was by ship. A few trading vessels visited San Francisco before 1849, but the Gold Rush brought in hundreds of ships from all over the world. Ships can transport exotic species (mainly invertebrates) in their ballast, or as fouling organisms, or bored into their hulls. The first recorded exotic species in San Francisco Bay (1853) was a fouling species, the Atlantic barnacle (Carlton 1979; Cohen and Carlton 1995).

In 1869, just two decades after the start of the Gold Rush, the Transcontinental Railroad was completed, providing another transport mechanism for exotic species introductions. Almost immediately trains began bringing shipments of Eastern oysters (*Crassostrea virginica*) for aquaculture in the Bay. Although the oysters grew well in the Bay, they did not establish a reproducing population (otherwise, *C. virginica* would be another exotic invader). However, many exotic species traveled as stowaways with the oyster shipments. A single oyster shell can carry dozens of species of invertebrates, and additional invertebrates may be associated with the mud and algae in which the oysters are packed (Carlton 1979). Another route for exotic species entry was opened up when oyster cultivators began bringing in the Japanese oyster, *Crassostrea gigas*, which was commercially grown in the Bay in the 1930s (Carlton 1979).

Crassostrea gigas, also known as Pacific giant oyster, has been a staple of California mariculture since 1929; it is the most common species of oyster grown on the west coast. Hatchery-spawned oysters are now raised in Tomales Bay and Drakes Estero. *C. gigas* was undetected in the Bay prior to 2004, when suspicious shells were found in the South Bay. Living oysters turned up two years later. *C. gigas* is known to outcompete and overgrow other bivalves, which could hinder efforts to restore the native *Ostrea conchaphila*. *C. gigas* could also hog estuarine food resources and reduce pelagic organisms.

C. gigas may have gotten a toe-hold after being planted illegally near San Rafael, from larvae drifting in from rearing sites or hitchhiking on ballast tanks, or from three programs that used oysters in bioaccumulation studies. Some studies indicate that *C. Gigas* spawning is limited by temperature, but oysters spawn in the Bay and have all along. Larvae hadn't settled in at an effective rate until recently; isotopic analysis of oysters collected in 2006 indicated that they were four years old. Increased phytoplankton blooms in the Bay may also have contributed to their growth.

In a 2006 survey, volunteers collected more than 260 giant oysters between Dumbarton Bridge and San Leandro Marina. During a 2008 survey most of the high priority sites listed in the 2008 priority list as well as a few sites listed as mid- or lower priorities were surveyed. In May, the eastern portion of the San Mateo Bridge, the South Bay Wreck, and some bridges and pipeline crossings south of Dumbarton Point were surveyed by kayak. The western portions of the Dumbarton and San Mateo Bridges, which were on the high priority list, were not surveyed.

In May 2008, approximately 1,000 illegally-planted exotic oysters were removed by fish and game officials from a site in the Loch Lomond area near San Rafael. The Department of Fish and Game suspects that the landowner had removed substantial quantities of oysters in the weeks prior to this visit.

With the exception of the Loch Lomond oysters, nearly all of the exotic oysters were found in the southeastern portion of the Bay from around Dumbarton Point to around Hayward Landing, with a few found around the periphery of this area. Within the area, progressively smaller numbers of exotic oysters were found as the area was resurveyed. No evidence was found of a more recent year class having settled since oyster removal began in 2006, and there was no evidence of a subtidal population. (Cohen email communications to M. Latta, 2009; ESTUARY newsletter, October 2007).

Of the exotic species in San Francisco Bay and Delta whose route of introduction is known, about 52 percent were introduced by ships (ballast, fouling, or boring);

about 19 percent through shipping of oysters, and about 9 percent through fish or shellfish stocking by government agencies (Cohen and Carlton 1995). Other past and present mechanisms of introduction include shipments of lobsters and live bait from the East Coast, accidental or intentional release by individuals, and intentional release for biocontrol (Cohen and Carlton 1995).

Some important exotic invasives

The two exotic species with the greatest known negative impact on San Francisco Bay have been the Atlantic shipworm (*Teredo navalis*) and the overbite clam (*Corbula amurensis*). *T. navalis* destroyed about 50 major wharves, ferry slips, and other wooden structures in the northern part of Bay between 1919 and 1921 (Cohen and Carlton 1995). The effects of shipworms and other boring organisms are presumably much less today because of anti-borer treatment methods (Carlton 1979), although there are no recent studies of this issue.

The overbite clam (*Corbula amurensis*), first seen in the Bay in 1986 and now the dominant benthic organism in the North Bay, is a voracious filter feeder that can filter the entire water column more than once per day. Since *Corbula* became established, the North Bay's normal phytoplankton blooms have virtually disappeared (Cohen and Carlton 1995). This invader is found in the South Bay as well, but its effects there have been less severe.

The non-native cordgrass *Spartina alterniflora* was introduced in the early 1970s for an experimental marsh restoration project (Cohen and Carlton 1995). This species hybridized with the native cordgrass, *S. foliosa*, and the offspring in turn hybridized with each other and with the parent species to produce a robust suite of hybrids, or "hybrid swarm" (Invasive Spartina Project 2007). The hybrids outcompete the native cordgrass and are also able to grow at lower elevations, thereby converting mudflats to vegetated wetland (Cohen and Carlton 1995). As of 2005, nearly 1,400 acres of Bay mudflats and marsh (or about 2% of the approximately 70,000 total acres of mudflat and marsh in the estuary) were infested with invasive *Spartina,* predominantly the hybrid form (Invasive Spartina Project 2007). The most impacted area is the South Bay. Three other exotic *Spartina* species are also found in the Bay, but in much smaller amounts (Invasive Spartina Project 2007).

The New Zealand boring isopod *Sphaeroma quoyanum* may be significantly eroding the Bay margin (Cohen and Carlton 1995). The Chinese mitten crab (*Eriocheir sinensis*) spread rapidly after its 1992 introduction, raising concerns because burrowing by this species has caused damage to levees in other regions. Currently, however, mitten crab numbers are low and impacts insignificant (San Francisco Estuary Project 2006). Other exotic species have probably had significant negative impacts that have not been studied or documented (A. Cohen, pers. comm.). There is no published evidence of an invasive exotic species causing a native species to become extinct in San

Francisco Bay; however, some exotics have greatly reduced the populations of some native species (A. Cohen, pers. comm.).

Not all the effects of introduced species are negative. Striped bass, American shad, catfish, and soft-shell clams all supported commercial fisheries in the past and are harvested recreationally today (Cohen and Carlton 1995).

Rate of invasion

The rate of invasion is apparently increasing. Between 1851 and 1960 approximately one new species per year, on average, was reported, whereas the average since that time is one new species every 14 weeks (Cohen and Carlton 1998). This rate is likely to increase even more with expanding global trade and travel.

Prevention and control

Efforts at prevention and control are still in early stages. The latest version (2006) of California's Coastal Ecosystem Protection Act sets strict standards, slated to be phased in between 2009 and 2016, for the concentrations of living organisms permitted in ballast discharges (A. Cohen, pers. comm.). Early efforts to control invasive *Spartina* indicate that digging and covering are effective in small areas, and the herbicide imazapyr shows promise for larger areas (Invasive Spartina Project 2007).

FRESHWATER DIVERSIONS

The 19th century may have witnessed such ecosystem-changing activities as gold mining, land reclamation, and rapid urbanization, but the 20th century can claim credit for the vast system of dams, reservoirs, aqueducts, and pumping plants that intercept, store, and redirect California's water, irrigating the state's crops and supplying water to its cities and industries. These water projects also exert major control over freshwater input into San Francisco Bay, transforming it into what Philip Williams has termed "the largest 'regulated' estuary in the world" (Williams 2000).

Water Projects Timeline

1923-1929 – Construction of seven large dams, with storage capacity >100,000 acre-feet, on Sierra rivers

1945 –Completion of CVP's Shasta Dam, creating the largest man-made reservoir in California (storage capacity 4.55 million acre-feet)

1951 – CVP's Tracy Pumping Plant goes into operation. California authorizes Feather River Project, which later becomes State Water Project (SWP)

1961 – Construction begins on SWP

1968 – Completion of SWP's Oroville Dam (storage capacity 3.5 million acre-feet) and Banks Pumping Plant

1971 – First SWP water delivery to southern California

1973 – Completion of California Aqueduct; longest stretch of freshwater in California

1979 – Completion of CVP's New Melones Dam on Stanislaus River

1992 – Central Valley Project Improvement Act enacted

Principal sources: CA DWR web site, US Bureau of Reclamation web site

Small-scale irrigation in the Central Valley began soon after the Gold Rush. Starting in the late 1880s, irrigation districts were formed to make possible the coordination and funding of larger projects (Bay Institute 1998). These early diversions were so-called direct diversions in which water is not stored for more than 30 days (Maureen Sergent, DWR, pers. comm.). The diversion of irrigation water from streams during the dry summer months, when flows were already low, decreased freshwater input into the Delta during summer and fall, causing increased salinity intrusion (Trends in Hydrology).

The era of large-scale water engineering began with O'Shaughnessy Dam on the Tuolumne River, completed in 1923. By 1929 dams with over 100,000 acre-feet of storage capacity had been built on six additional Sierra rivers, mainly in the San Joaquin drainage basin. The dams on the Tuolumne and Mokelumne were built to provide water for Bay Area cities; the others were for local irrigation and municipal use, flood control, and power generation (Bay Institute 1998). These large reservoirs are able to capture and store water from winter snowmelt, then release it gradually during the summer.

Statewide water projects
The projects built in the 1920s did nothing to bring water to farmers in the San Joaquin Valley, whose water needs were acute because most of California's precipitation and most of its rivers are in the northern half of the state. Subsequent decades brought two massive statewide efforts, the Central Valley Project (CVP) and the State Water Project (SWP), whose main objective was to move water from north to south (Williams 2006).

The CVP started out as the "State Water Plan," approved by the California legislature in 1933 (Monroe and Kelly 1992), but because of the Great Depression the state could not finance the project and in 1935 it was renamed and became a federally funded New Deal public works project under the Department of Reclamation. The CVP's main goals were to convey Sacramento River system water to the San Joaquin Valley for irrigation; to control Sacramento River flooding; and to control salinity incursions in the Delta by creating a hydraulic salinity barrier (Bay Institute 1998). CVP's Shasta Dam was completed in 1945, and the project's Tracy pumping plant went into operation in 1951 (DWR News Online 1999).

Construction on the SWP, which is operated by California Department of Water Resources, began in 1961. The SWP's major features are the Oroville Reservoir on the Feather River, the Harvey O. Banks pumping station at Tracy (completed in 1968), and the 444-mile-long California Aqueduct (completed in 1973), which conveys water to the San Joaquin Valley and southern California (DWR web site).

The CVP has about twice the storage capacity of the SWP (about 11 million acre-feet versus 5.8 million acre-feet), and more than double the maximum annual water delivery capability (9.3 million acre-feet for CVP as opposed to 4.2 million acre-feet for the SWP) (DWR web site). The CVP primarily supplies water for agriculture. During the 1970s and 1980s, SWP deliveries to agriculture exceeded urban deliveries, but since then urban deliveries have steadily increased (Peter Vorster). Currently about 70% of SWP deliveries are to urban users (municipal and industrial) in both northern and southern California (insert actually web address here).

Hundreds of smaller water projects, both public and private, also divert water from Central Valley rivers. As of the mid-1990s, a total of 660 dams had been constructed in Central Valley watersheds, with a total capacity of 30.7 million acre-feet (Bay Institute 1998).

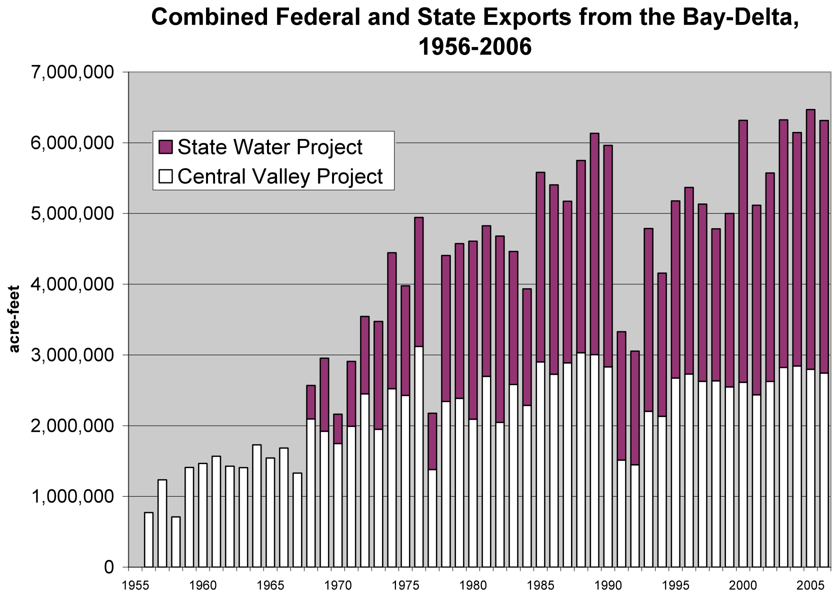
Quantity of freshwater inputs to Bay

Ninety percent of the freshwater entering the San Francisco Bay-Delta estuary comes from the Sacramento and San Joaquin rivers. This freshwater supply is diminished by (a) diversions above the Delta, (b) diversions within the Delta for in-Delta agricultural use, and (c) exports from the Delta.

Annual diversions above the Delta have increased from less than 1 million acre-feet in 1880 to about 9 million acre-feet in 1996 (Monroe and Kelly 1992, San Francisco Estuary Project 1997). That figure includes 4.5 million acre-feet diverted by the CVP. Most of the water diverted above the Delta is used for irrigation in the Sacramento and San Joaquin basins. Because some portion of the diverted water eventually returns to the rivers ("return flows"), the actual loss, or depletion, of freshwater that would otherwise enter the Bay is less than the total amount diverted and is difficult to measure directly.

The Delta serves as the hub for both the CVP and the SWP. Timed freshwater releases from the upstream reservoirs flow into the Delta, where they are drawn into CVP or SWP pumps and redirected (exported). Figure 1 shows how Delta exports increased from 1956 to 2006.

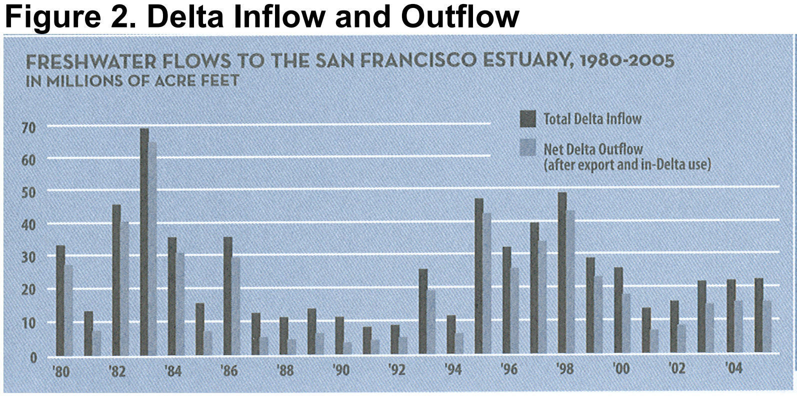
Figure 1. Delta exports, 1956-2006 (in acre-feet)



Graph courtesy of Environmental Defense; based on California DWR DayFlow data

Delta inflow is the amount of freshwater that reaches the Delta after upstream depletions, and Delta outflow is the amount that actually flows into San Francisco Bay. The difference between inflow and outflow reflects both in-Delta use (about 1 million acre-feet per year, mainly for irrigation) and exports by the CVP and SWP (shown in detail in Figure 1 above). Since 1974 (i.e., since completion of the water projects), this difference has been fairly constant in its absolute volume, generally ranging between 4 and 6 million acre-feet (San Francisco Estuary Project 1997). However, in dry years diversions and exports from the Delta take a much larger relative "bite," sometimes amounting to more than half of Delta inflow (Figure 2).

Figure 2. Delta Inflow and Outflow

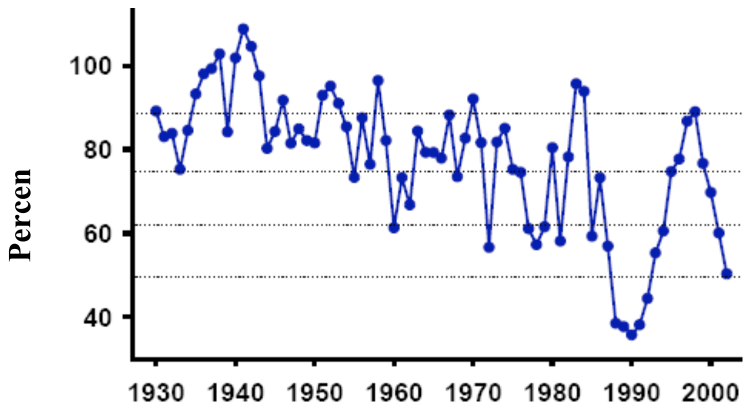


Source: SFEP 2006

As mentioned above, it is difficult to quantify losses of freshwater inflow upstream of the Delta. One measurement that incorporates these upstream freshwater depletions is the "Freshwater Inflow" indicator used in the Bay Institute's

Ecological Scorecard for San Francisco Bay (Bay Institute 2003b). This indicator is based on comparing actual Bay inflow with "unimpaired runoff," which is an estimate of the amount of freshwater that would enter the Central Valley in the absence of dams or diversions (note that this is not the same as natural or historic runoff). As shown in Figure 3, freshwater inflow has declined significantly since completion of the major water projects.

Figure 3. Freshwater Inflow. Percentage of "unimpaired" freshwater inflow from the watershed that actually enters San Francisco Bay



Source: Bay Institute 2003b
Caption: Freshwater Inflow (%) = actual inflow to Bay √ "unimpaired" inflow ∗ 100

Timing of freshwater inputs to Bay
California's system of water storage and delivery has altered not just the overall amount of freshwater reaching the Bay but the natural seasonal pattern of freshwater inflow. Under natural conditions, inflow was low during the dry summer and fall months; increased in winter due to rainfall, with occasional large-magnitude inflows during floods; and peaked in spring when there was a long period of high flows fed by the melting of the Sierra snowpack (Bay Institute 2003c). Under the current highly manipulated regime, freshwater enters the Bay at a more constant rate year-round, smoothing out the natural variability. In summer and early fall, Delta outflow into the Bay is increased compared to unimpaired conditions, and the rest of the time it is reduced. The reductions are greatest in dry years.

ACTIVITIES THAT REMOVE OR DISTURB BAY BOTTOM

Close to 4,000 commercial ocean-going vessels move through the Estuary each year, carrying over 75 million tons of cargo worth between $20-$25 million (San Francisco Estuary Project 2007). These ships depend on deepwater ports and shipping channels in the Bay and Delta that must be dredged each year to maintain navigability. The volume of material dredged annually from channels, ports, and marinas in the Estuary has decreased from approximately 8 million cubic yards (cy) in 1993 to just over 4 million cy as of 2006 (including the San Francisco Main Ship Channel outside the Golden Gate). The Oakland Harbor

Navigation Improvement Project is in progress, and the Baldwin Ship Channel is still under consideration. Few anticipated projects remain that involve large volumes of new dredging work; however, as smaller marinas around the Bay strive to accommodate deeper draft boats, increased dredging and deepening activities may take place at those facilities (San Francisco Estuary Project 2007).

Vessel movement, docking, anchoring and propeller wash can cause some disturbance or alteration of bottom sediments and even of bedrock. Studies conducted at the Richmond Longwharf found that docking ships and barges stirred up large plumes of sediment (USACE 2005 cited in Cohen 2008, Appendix 2-1). During the geophysical investigation of Arch Rock conducted in 2000, deep gouges were noted that were thought to be possible anchor scars (Sea Surveyor 2001, cited in Cohen 2008, Appendix 2-1). Around 3,000-4,000 cargo vessels entered the Bay each year in 1977-1996 (Marine Exchange 1997, cited in Cohen 2008, Appendix 2-1). Although the cargo handled at San Francisco Bay ports is projected to more than double between 2000 and 2020 from less than 20 to over 40 million tons (exclusive of oil and oil products, bulk sugar, and Hawaiian molasses), the number of ship calls will decline as the average ship size increases (BCDC 2003, cited in Cohen 2008, Appendix 2-1). Other things being equal, bottom disturbance by ships may become less frequent (fewer ships) but produce greater disturbance per event (larger, deeper-draft ships).

Dredged material from navigation channels was historically disposed of at various in-Bay disposal sites and expected to disperse with the currents and tidal action. In the 1980s, dredged material deposited near Alcatraz Island, a primary disposal site, mounded and did not disperse as expected, creating concerns about impacts on aquatic organisms and water quality. In the 1990s, the Long-Term Management Strategy (LTMS) for the Placement of Dredged Material in the San Francisco Bay Region was developed by Bay regulatory and resource agencies and numerous stakeholders to better manage dredging and disposing of dredged materials in the Bay. These agencies also worked with the U.S. EPA to establish a deep ocean disposal site as an alternative to in-Bay disposal. Since 1993, the LTMS has re-used approximately 8 million cy of dredged materials in projects such as the Hamilton wetlands, the Oakland Middle Harbor Enhancement Project, Sonoma Baylands, Montezuma wetlands restoration, and a demonstration beach nourishment project at Ocean Beach (San Francisco Estuary Project 2007). Despite those re-use projects, however, some in-Bay disposal of dredged material still occurs.

In addition to the dredging of ship channels, the Bay is also dredged (mined) for sand and shell, activities that may alter the Bay’s floor. Commercial sand mining in the Bay began in the 1930s, to obtain marine aggregate for use in commercial construction—e.g., of bridges, freeways, and buildings. Over 1-1.5 million m^3 of sand and gravel was dredged in 1912-1915 from Presidio Shoal to create San Francisco's Marina District (Chin et al. 2004 cited in Cohen 2008, see Appendix

2-1). Sand mining with hydraulic suction pumps began in the Northern channels of the Bay in the 1930s, and in the Central Bay in the 1950s (Hanson et al. 2004, cited in Cohen 2008, see Appendix 2-1). Currently, around 1.2 million m^3 of sand is mined from the Bay each year by three marine aggregate companies that collectively operate barges. About 90% is taken from the shoal areas of the West Central Bay at depths of 10-30 m, and about 10% from the main Suisun Bay channel between Benicia and Chipps Island at depths of 5-15 m (Hanson et al. 2004, cited in Cohen 2008). The volume of sand that can be harvested from these areas has been specified in state permits issued by the State Lands Commission and the Bay Conservation and Development Commission (BCDC), and federal permits by the U.S. Army Corps of Engineers. These agencies also evaluate any proposals to expand mining activity within the Estuary. Any increase in mining is subject to environmental review under the California Environmental Quality Act (CEQA) and the National Environmental Policy Act (NEPA). During the period March 2002-February 2003, 1.3 million cy of sand were harvested from the central Bay; almost 260,000 cy from Carquinez Straight and Middle Ground Shoal; and almost 97,000 cy from eastern Suisun Bay. This level of harvest is typical of sand harvest from the Estuary in recent years (Hanson Environmental 2004a).

Dredging for sand is done in shallower waters because coarser sand, which is a better construction product, is located in shallow and high velocity current areas where the sand is naturally replenished (San Francisco Estuary Project 2005). The mining is clustered in specific areas, characterized by high river or tidal velocities and sand deposits having a low percentage of fine material (silts, clay, and mud). Sand miners use a trailing arm hydraulic suction dredge and hopper barge; using methods ranging from “moving pothole” to trolling to stationary potholes. Mining events last between three and five hours, during which time 1,500 to 2,500 cy of sand is harvested. During the mining operation, water is taken into the suction head, creating a water and sand slurry to mobilize the sand and pump into the hopper barge (Hanson Environmental 2004a). During the 2002-2003 Hanson Environmental study, the minimum water depth where mining occurred was 17 feet and maximum depth 96 feet although sand mining can occur in shallower or deeper waters. During sand mining, an overflow plume of water, combined with fine grained sediment, air bubbles, plankton, and other materials, is discharged, increasing suspended sediment concentrations behind the mining barges. The overflow plume typical dissipates within three to four hours after operations, but sand mining does result in temporary localized changes in water depths and benthic habitat (Hanson Environmental 2004a). In the central Bay, subtidal habitats directly affected by sand mining consist primarily of deepwater benthic habitats generally with low vegetation and detritus. In upstream mining locations, sand harvest occurs in open navigation channels and generally affects deeper channel bottom substrates. There, sand mining does not occur in shallow water subtidal and intertidal habitats (Hanson Environmental 2004a).

Shell—relic 2,300-2,500 year-old native oyster shell (*Ostrea conchaphila*)—is harvested primarily from the south Bay, with only one shell mining company operating today (Chuck Hanson pers. comm.) From the mid 1920s through the 1980s, most of the oyster shell was mined and used as a raw material in cement manufacture. Between 1924 and the mid-1960s, an estimated 25 to 30 million tons of shell was mined from the South Bay (Hanson Environmental 2004b). Today, approximately 65,000 cy are harvested per year, from one site north of the San Mateo Bridge. The shell is used primarily as a calcium supplement in poultry feed and human supplements (Brenda Goeden, BCDC, pers. comm.). Oyster shell mining results in the localized removal of relic shell from the subtidal area as well as a redistribution of silt and mud that is washed from the shell and returned to the area. These effects contribute to localized changes in bathymetry (water depth) and sediment grain size distribution (Hanson 2004b). Oyster shell mining uses the trailing suction method of trolling, in which shell deposits are mined from near the substrate surface (typically within approximately 6 inches of the surface) by slowing trolling over the deposits within the lease area. Speed is kept between one and two knots while two suction pipes are lowered to the bottom (water depths in the mining area typically range from 15 to 20 feet deep). The suction pipes are connected to pumps, which transport a shell, water, and silt slurry from the Bay bottom up to a set of two trammels—rotary screens—for washing and screening. The shell is then pumped to the barge from the trommel. Silt removed from the shell and wash water from the trommel are discharged overboard using two submerged discharge pipes, resulting in a localized sediment plume. The suspended sediment concentrations and aerial extent of the plume vary based on a number of factors, including the quantity of silt and mud associated with a specific shell deposit, tidal currents, and naturally occurring ambient suspended sediment concentration within the south Bay in the area where mining occurs (Hanson 2004b).

Channel dredging, sand mining, and shell mining all have several potential consequences: the removal or killing of organisms living in or on the sediments; the short-term or long-term alteration of bottom habitat; hydrodynamic changes; the release of buried organic matter, nutrients or contaminants; short-term increases in suspended sediment concentrations; and the subsequent settlement of suspended sediments (Cohen 2008, Appendix 2-1). Dredging and sand mining can also cause localized changes in species composition and abundance of benthic macroinvertebrates. Since benthic areas have been found to be rapidly recolonized by macroinvertebrates following disturbance, as well as subjected to increased foraging by fish, it is possible that frequent disturbance from maintenance dredging and sand mining could help non-native invasive species spread and colonize disturbed benthic habitats (Hanson Environmental 2004a).

An immediate impact of dredging or bottom mining is the loss of organisms that cannot escape removal by mechanical or hydraulic (suction) dredges.[1] (See

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[1] Dredging results in at least a local depletion of these organisms. One study reported 99% mortality of fish entrained in pipeline dredges (Levine-Fricke 2004), while the mortality of

Cohen 2008, Appendix 2-1for more detail). Sites defaunated by the removal of sediments are subsequently colonized primarily by the lateral movement of organisms and by settlement of planktonic (larval) forms. The initial colonizers are often opportunistic species that differ from those that were present prior to sediment removal; however, over time, the new biotic community often comes to resemble the pre-removal community (Cohen 2008, Appendix 2-1).

Longer term changes may result from modifications to habitat or topography. Natural sediment deposits may have a complex structure, including vertical variation in particle size; bacterial or algal mats stabilizing the surface; tubes, burrows or pits created by various organisms; and accumulations of fecal pellets (Cohen 2008, Appendix 2-1). It can take some time to rebuild this structural complexity after disturbance or removal of the surface sediment. A permanent change in habitat may result if the area refills with sediment of a different grain size and composition than was present before the dredging or mining activity; if significant biogenic structures do not re-establish; or if the area does not refill to its pre-existing elevation. Once a depression is formed, it may be maintained by tidal currents that inhibit sedimentation or cause erosion (Cohen 2008, Appendix 2-1). It is not known how long the depressions caused by dredging or bottom mining last. One study reported that intertidal pits 1 m x 4 m x 0.1 m-deep filled in completely within about 100 days if dug in sand but had not filled in after more than 200 days if dug in muddy sand or mud; the rate at which the pits refilled with sediment declined linearly with the increase in silt and clay content (see Cohen 2008, Appendix 2-1).

Reductions in bottom elevation caused by dredging or mining can cause changes in the hydrodynamic regime, which can in turn affect areas that are outside of the sediment removal zone (Cohen 2008, Appendix 2-1). These hydrologic changes include the intrusion of salty bottom water farther upstream; alterations in tidal ranges, tidal prisms or tidal currents; and changes in erosion patterns and consequent suspended sediment loads (ABP Research 1999 cited in Cohen 2008). Upstream salt intrusion has been noted as a potential or actual consequence of channel dredging in the Bay's northern reach and Delta (Cohen 2008, Appendix 2-1).

HARVESTING OF AQUATIC RESOURCES

Dungeness crab (*Cancer magister*) entrained by dredges ranged from 5%-100% depending on the type of dredging operation and the size of the crab (Wainwright et al. 1992; Nightingale and Simenstad 2001). Some invertebrate or algal species may fare better. If some organisms do survive the dredging, transport and disposal process, then the initial net impact of channel dredging on these organisms would be to remove them from the dredge site and transfer them to the disposal site, rather than to kill them. Whether they then survive and reproduce would depend on their condition and their response to their new environment. Note that the survival of these organisms is not necessarily a desirable outcome (depending in part on the distance between dredge and disposal sites), as it could faciliate the spread of non-native species or exotic genetic material between dredge and disposal areas.

The Estuary supports an abundant and diverse community of fish, macroinvertebrates, and other aquatic resources (NMFS 2007). Otter trawl, midwater trawl, and plankton surveys conducted by the California Department of Fish and Game at selected stations within the Estuary between 1980 and 2001 near sand-mining areas found the most frequently occurring fish and invertebrates within the Central Bay to be northern anchovy, Dungeness crab, Bay shrimp, California halibut, Pacific herring, striped bass, and Chinook salmon (Hanson Environmental 2004a). In the Carquinez Strait and Suisun Bay areas, the surveys also included white sturgeon, American shad, and white catfish.

Although the Estuary and its watershed once supported enormous populations of salmon and other species (e.g., cod, sardines, smelt, herring, rockfish, shad, flounders), those fisheries began to be harvested with gillnets and seines at around the time of the Gold Rush (The Bay Institute 1998). Between 1870 and 1915, fisheries in the Bay reached maximum production: almost every species fished commercially was taken in record quantities (Skinner 1962). Overfishing depleted certain stocks as early as 1878, and most fish canneries had gone out of business by 1916. Other major fisheries that were overharvested during the late 19^{th} and 20^{th} centuries were those for sturgeon, sharks and rays, Bay shrimp, clams, mussels, and oysters. The only fishery that has proved sustainable is herring, probably because demand was low early on and because herring have an unusually high reproduction capacity (The Bay Institute 1998).

For many years, the Bay supported a viable shellfish fishery, and has been described as having the greatest potential of any area in the state for shellfish culture (Skinner 1962). Between 1870 and 1915, Chinese settlers harvested the native Bay shrimp (*Crangon franciscorum*) in great quantities, both in the north and south Bays, taking five million or more pounds per year. The Chinese shrimpers used flat-bottomed canoes made of redwood to maneuver in shallow water, dropping 30 or more “bag” or “trap” cone-shaped nets about 42-feet long nets side by side into the water. The nets were held open with a combination of weights on one side and floats on the other. The wide end of the cone faced the current, and the shrimp, which cannot swim against a current, were trapped as the water moved through the bags. In the late 1890s, daily catches averaged 7,000 pounds per boat (Postel 1988). Later, larger boats were used. A series of restrictions was placed on the Chinese shrimp fishery starting in 1901, and in 1911 set nets were prohibited only to be allowed again in the South Bay in 1915. Beam trawling for shrimp started in 1914-1921, mainly in San Pablo Bay, and steadily grew in volume while set net shrimping continued for a time in the South Bay. By the late 1920s, San Pablo Bay trawlers were catching nearly 800 tons of shrimp, compared to a South Bay set net catch of only 200 tons. Shrimp landings remained at around 1,000 tons/year through the 1930s, dropped to around 400 tons in the 1950s, and have been under 100 tons, sold mainly for bait for striped bass and sturgeon sport-fishing, since the mid-1960s. There were 19 boats trawling for shrimp in the Bay in 1930, and 15 boats in the late 1970s; by the mid-

1990s, however, there were only seven licensed shrimp boats in San Pablo and Suisun bays and two in the South Bay (Clark 1930; Skinner 1962; Smith and Kato 1979; CDFG license data, cited in Cohen 2008, Appendix 2-1).

Oysters were another huge fishery in the late 1800s and early 1900s. The native oysters (*Ostrea conchaphila*) were harvested since the days of Spanish colonization. They were taken from their natural beds until the introduction of the Eastern oyster, which became more popular. Deposits of shells from the native oyster were once extensive all along the western part of the Bay, where they formed a "white glistening beach that extends from San Mateo for a dozen or more miles southward" (Skinner 1962). The abundance of these shells was considered infinite, and schooners would carry loads of them away for use in making garden paths—and later cement (see shell harvesting section). Eastern oysters (*Crassostrea virginica*) became important in about 1870, grew favorably in the Bay—particularly the south Bay, where entrepreneurs acquired underwater lands for oyster beds—and expanded to a million dollar a year industry. Oyster growers cut hills and filled valleys in these underwater lands to create level beds, and then spread a layer of freshly washed shells on top of it, to provide a surface for the young oysters arriving from the East Coast (Postel 1988). These nursery beds were located in protected areas where storms and currents rarely disturbed the bottoms; when the oysters reached a larger size, they were transplanted to rearing areas off Millbrae and San Mateo where the tides moved more swiftly and brought more floating food past the quickly fattening mollusks (Postel 1988). Mature oysters were then harvested by men working on flat-bottomed scows using rakes to bring the oysters up from the Bay floor. But increased sewage and ship travel in the Bay starting in the early 1900s caused the oyster fishery to decline rapidly (Skinner 1962).

Clams and mussels were productive and popular as well; in 1865 annual clam production surpassed 2.5 million pounds (Skinner 1962). The eastern softshell clam was introduced by accident along with the eastern oyster and became very abundant; more than 1.5 million pounds a year were taken from San Pablo Bay and the south Bay. The crab fishery was also very important—in 1892 crab landings rose to an estimated 2,750,000 pounds—but moved to the sandy bottom shallow waters off of the Golden Gate before 1900.

Today the estuary's commercial fishery is much reduced. Pacific herring is the only species of great commercial value harvested in the Bay (San Francisco Estuary Project 1992). Northern anchovy are taken for bait as are Bay shrimp; Chinook salmon spend parts of their lives in the estuary but are commercially harvested in the ocean. The estuary's sport fishery is much more diverse, and supports about 4.4 million recreational use-days annually (San Francisco Estuary Project 1992). Species caught by sport fishers include striped bass, Chinook salmon, halibut, starry flounder, brown rockfish, sturgeon, surfperch, lingcod, jacksmelt, topsmelt, white croaker, shark, ray, and skate. In the Delta and upstream, sport species include Chinook salmon, striped bass, American shad, steelhead trout, white catfish, largemouth bass, and bluegill. In recent years, there has been a serious decline of Delta smelt, threadfin shad, longfin smelt, and striped bass in the Delta, prompting a flurry of new research and emergency water management measures. So far, no one cause has been identified: the decline is suspected to be a result of poor water quality, water diversions, invasive species wreaking havoc in the food web, and algal blooms.

One commercial harvesting activity involves trawling the bottom of the Bay to catch demersal fish or invertebrates. Bottom trawling and beach seines are often used for research and education in the Bay. The California Department of Fish and Game Bay-Delta Monitoring Program has used an otter trawl to conduct monthly sampling at 35-52 sites in the Bay and western Delta since 1980, and used beach seines at 27 shoreline sites in the Bay each month from mid-1980 through 1986 (see Cohen 2008, Appendix 2-1). The Marine Science Institute, an educational organization, has trawled in the South Bay for 35 years, conducting typically 200-400 otter trawls per year (see Cohen 2008, Appendix 2-1). Many other research, monitoring and education programs drag nets along the bottom of the Bay.

Trawling churns up and turns over sediments. In addition to removing target species and by-catch, trawling crushes, buries or exposes organisms, which attracts predators and scavengers. Structural complexity in the sediment can be disrupted see Cohen 2008, Appendix 2-1). The small-scale structural features destroyed by trawling can be of great importance to bottom biota and demersal fish; the destruction may affect biogeochemical exchange processes between sediments and the water column (see Cohen 2008, Appendix 2-1).

Overall, studies suggest that bottom fishing has not had a large impact on bottom habitat in San Francisco Bay, at least in recent decades when commercial trawling has been limited to a small bait shrimp fishery (see Cohen 2008, Appendix 2-1). However, there has been no quantification of the historic or current levels of fishing impacts on the bottom in terms of the distribution, acreage and frequency of trawling in the Bay. Second, impacts from trawling are believed to be substantially greater on biogenic substrates (see Cohen 2008, Appendix 2-1). In San Francisco Bay these include eelgrass, algae, and oyster beds, and very little information exists on the initial extent and distribution of these beds or on their later historic or current distribution and extent relative to trawling activities.[2] Trawling also removes fauna and flora that are important sediment stabilizers, including tube-building amphipods (such as *Ampelisca*

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[2] One indication that there may have been some significant overlap between trawling sites and biogenic substrates comes from Ganssle (1966) who noted that in 1963-64 the tunicate *Molgula manhattensis* (reported as *M. verrucifera*) was "so abundant in San Pablo Bay bottom tows that it was impossible to haul the trawl aboard by hand." *Molgula* attaches to hard surfaces or vegetation and does not live on sediment, and the most likely substrate for the *Molgula* filling the trawl nets in San Pablo Bay was the seaweed *Gracilaria* (personal observations). Reserach trawling may thus have had some impact on *Gracilaria* beds.

abdita) and polychaetes (such as *Sabaco elongatus*).[3] *Ampelisca* are removed in such numbers that the Department of Water Resources (research trawling) and Marine Science Institute (educational trawling) have moved transects to avoid beds of *Ampelisca*, which can completely clog nets (see Cohen 2008, Appendix 2-1).

NUTRIENTS

Nutrients are elements that organisms use for metabolism and growth. They occur in living organisms, in the wastes and dead organic matter derived from them, and as molecules in the environment. Concerns can arise when anthropogenic changes either deplete nutrient availability, restricting productivity, or increase nutrient supply, causing excessive growth of autotrophs. Several human activities—including land clearing, the use of fertilizer, the discharge of human and animal wastes, and the burning of forests and fossil fuels—increases the flow of these nutrients into lakes, rivers and coastal waters (Cooper and Brush 1991, cited in Cohen 2008, Appendix 2-1). Increased loadings of these nutrients into coastal waters has sparked algal blooms, decomposition, and oxygen depletion in bottom waters and sediments (Howarth 1988; Nixon 1995, cited in Cohen 2008, Appendix 2-1). Other effects can include reduced water transparency; declines in perennial seaweeds and sea grasses and the promotion of fast-growing, ephemeral seaweeds; increases in blooms of toxic dinoflagellates; changes in the diversity and abundance of benthic invertebrates; a shift to anaerobic metabolism, stimulation of sulfate reduction and production of metal-sulfides and hydrogen sulfide in the sediments; seasonal shifts in the timing of phytoplankton growth; and possibly a shift to smaller demersal fish species (Cloern 2001, cited in Cohen 2008, Appendix 2-1).

In San Francisco Bay, there have been occasional incidents of nuisance algal blooms, oxygen depletion, foul (hydrogen-sulfide) smells and/or fish kills (e.g. Horne and McCormick 1978; Nichols 1979; Luoma and Cloern 1982; Cloern and Oremland 1983; Josselyn and West 1985, cited in Cohen, Appendix 2-1). However, most of the time, light availability or benthic grazing appears to control algal growth in the Bay (Cloern 1979; Alpine and Cloern 1988; Cloern 1982; Nichols 1985; Jassby et al. 2002; Cloern et al. 2007, cited in Cohen 2008, Appendix 2-1).

Since the construction of secondary treatment facilities for municipal wastewater in the 1970s and 1980s, hypoxic occurrences have become rare in San Francisco Bay, even though nutrient levels in the Bay have generally remained high (Nichols et al. 1996, cited in Cohen, Appendix 2-1). Unlike many temperate-zone estuaries, management concerns in the Bay have focused on the issue of low primary productivity and its impact on food webs, rather than on the stimulation of excessive primary productivity (Cloern 2001, cited in Cohen,

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[3] These are both exotic species, as are some of the other common sediment-stabilizing species in the Bay.

Appendix 2-1). There has thus been relatively little research on nutrient loadings and their impacts.

Two recent lines of inquiry have begun to change or at least modify this view of the Bay. Records of increasing phytoplankton densities in South, Central and San Pablo bays since the late 1990s (Cloern et al. 2006, cited in Cohen 2008, Appendix 2-1) have led to consideration of conditions under which the Bay's "eutrophication resistance" could be reduced and the Bay might begin to respond to nutrient inputs (Cloern et al. 2007, cited in Cohen 2008, Appendix 2-1). Meanwhile, other researchers argued that ammonia, normally considered a nutrient, also has an inhibitory effect that limits productivity in the Bay by limiting the uptake of nitrate; and that changes in wastewater treatment processes have affected ammonia inputs and productivity in the Bay (Wilkerson et al. 2006; Dugdale et al. 2007, cited in Cohen 2008, Appendix 2-1).

CLIMATE CHANGE AND SEA LEVEL RISE

Possibly the biggest threat to the Bay and its subtidal habitat is sea level rise associated with climate change. A March 2009 report by the Pacific Institute (Heberger, et al. 2009) found that under medium to medium-high emissions scenarios, mean sea level along the California coast will rise from 1.0 to 1.4 meters—or four and a half feet—by the year 2100. A one-meter sea-level rise would threaten commercial, residential, and industrial structures around the Bay valued at $48 billion (year 1990 dollars); substantial areas of wetlands around the Bay could be damaged or lost. A rise in sea level of 1.4 meters would flood approximately 150 square miles or land immediately adjacent to current wetlands, which could potentially create new wetlands if those areas are protected from development. The report suggests that local ordinances, statewide coastal development policies, and land conservation purchases offer ways to protect those lands as buffer zones.

Climate change and sea level rise will also likely have an impact on sediment in the Estuary. Sea level rise will tax an already taxed system—the Estuary is likely to keep deepening in the future as sediment demand from sea level rise outpaces sediment inflow (Jaffe, *Pulse of the Estuary*, SFEI 2009).

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