Final Draft

White Paper

Potential Impacts of Dredging on Pacific Herring in San Francisco Bay

Prepared for:

U.S. Army Corps of Engineers
South Pacific Division
and
Long-Term Management Strategy
Science Assessment and Data Gaps Workgroup
Herring Subcommittee

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1. Introduction

One of the last remaining urban commercial fisheries on San Francisco Bay, the Pacific herring accounts for approximately 3000 tons of roe harvested each year. Pacific herring are also forage for other animals, so the population is of interest to resource agencies and conservationists. Meanwhile, millions of cubic yards of sediment are dredged from San Francisco Bay annually to maintain the navigation channels and marinas needed to support the shipping and boating industries of local ports and harbors. Herring spawn in many of the same areas that are maintained by dredging, which fosters concern that dredging activities could harm the species or the fishery.

Since 1990, the U.S. Environmental Protection Agency (USEPA), U.S. Army Corps of Engineers (USACE), State Water Resources Control Board (SWRCB), San Francisco Bay Regional Water Quality Control Board (SFBRWQCB), and the Bay Conservation and Development Commission (BCDC) have worked together with navigation interests, fishing groups, environmental organizations, and the interested public to establish a Long-Term Management Strategy (LTMS) for dredging and dredged material disposal in the San Francisco Bay area. The Department of Fish and Game (DFG), the U.S. Fish and Wildlife Service (USFWS), and the National Marine Fisheries Service (NMFS) have participated in the LTMS process from its inception. In 1998, the LTMS agencies published a *Long-Term Management Strategy for the Placement of Dredged Material in the San Francisco Bay Region: Final Policy Environmental Impact Statement/ Programmatic Environmental Impact Report*.

One approach used to reduce potential adverse impacts from dredging on marine life has been the implementation of "environmental work windows," periods in the year when specific marine organisms are presumed to be least vulnerable to possible impacts. Environmental windows are included in USACE permits to dredge, and most windows are based on consultation with NMFS and USFWS, under the auspices of the federal Endangered Species Act, and with DFG under the California Endangered Species Act (CESA). Opinions of DFG are also considered in the water quality certification process, which regulates discharges of dredged material. The National Environmental Policy Act and Essential Fish Habitat legislation also apply.

The Pacific herring is not an endangered species in California, but its roles as a commercial species and a forage fish are of concern to the state. The DFG concerns provided the rationale for environmental work windows for the species, presented in a September 22, 1993 letter from John L. Turner of DFG to Calvin Fong of USACE:

> "The DFG has substantial concerns regarding the potential for dredging activities, which occur in the vicinity of herring spawning activity and deposits, to negatively affect reproductive success. Adverse impacts to herring eggs or early larval forms may be generated by either the physical or chemical nature of the sediments that become suspended at the dredging site. These impacts include, but are not limited to: interference with attachment, fertilization, or respiration of the egg by sediment particles; the presence of sulfides and reduced oxygen levels in the water column; and the exposure to chemical contaminants which tend to be associated with the finer-grained sediments of the Bay. All of these elements, individually or in combination, can increase mortality and abnormality rates in the hatching embryos. It is important to note for regulatory purposes, that these effects are most likely to occur at the dredging site, which is frequently adjacent to the shoreline structures attractive to the spawning herring."

The environmental work windows are designed to protect spawning behavior and eggs and allow dredging from March 2 through November 30. Dredging is currently prohibited between December 1 and March 1, the period in which peak herring spawning occurs in San Francisco Bay (Figure 1-1).

At an August 11, 2004 meeting, a subcommittee of the LTMS focusing on herring identified several other possible effects of dredging activities on Pacific herring. These possible effects included effects of noise, presence of dredging equipment, or turbidity on the behavior of schooling or spawning adults, larvae, and juveniles. The group also noted that effects of disposal of dredged material in the Bay were possible, although risks from dredged material disposal are not part of the rationale for the environmental window, since disposal activities occur away from known spawning areas.

The goal of environmental work windows is to provide a high degree of protection to resources, but they can cause difficulties in scheduling needed dredging projects. A *Framework for Assessment of Potential Effects of Dredging on Sensitive Fish Species in San Francisco Bay* (LFR 2004), developed for the USACE, addresses the potential effects of dredging on fish (Figure 1-2) and stakeholder concerns regarding environmental work windows. Some of those concerns suggest that the Pacific herring windows are too restrictive, that information used to create them was tenuous, and that adequate or perhaps even better protection may be given by alternative strategies.

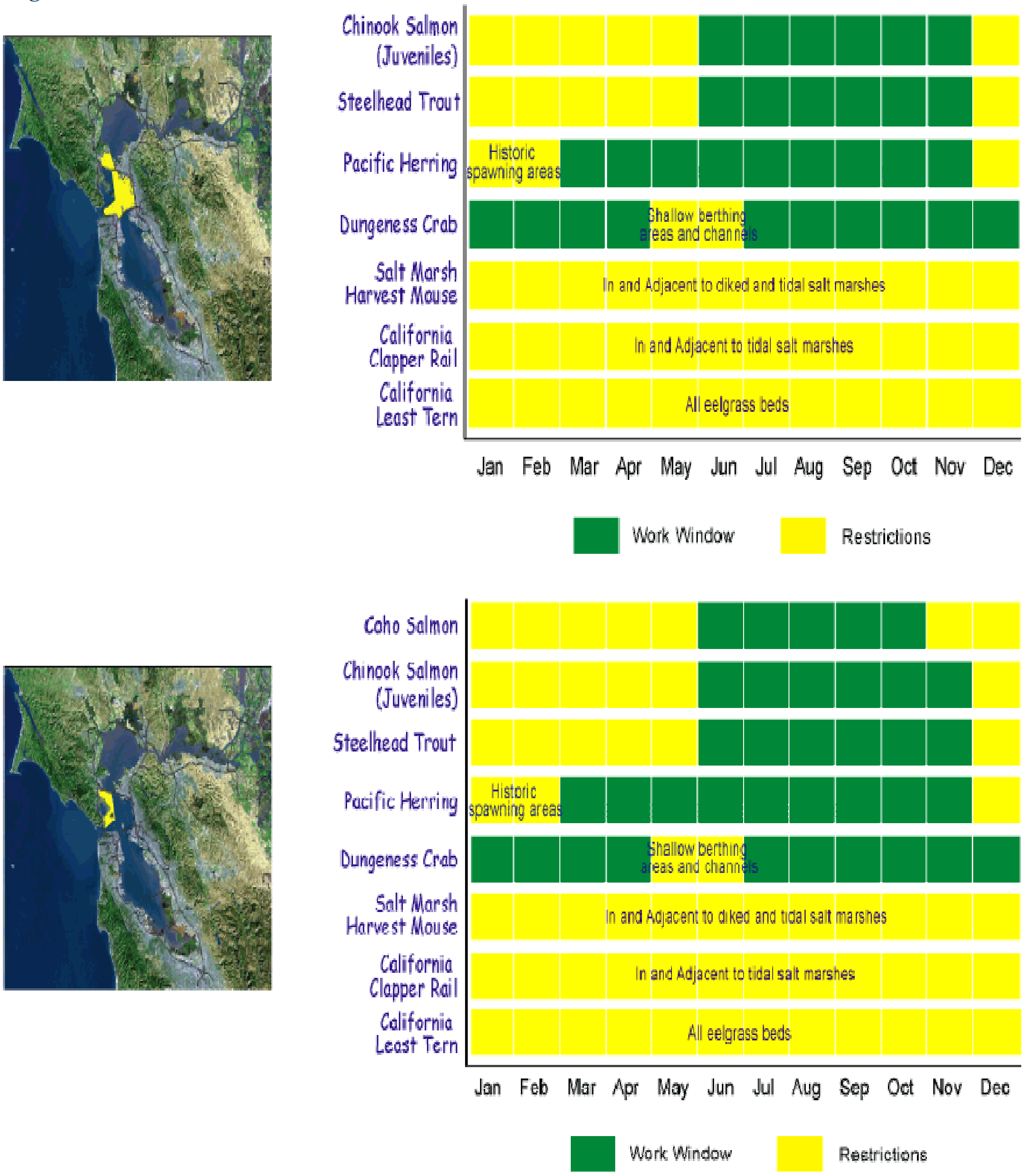

Figure 1-1. Environmental work windows for central San Francisco Bay and Marin County Yellow=restricted periods; green=work periods (from LTMS).

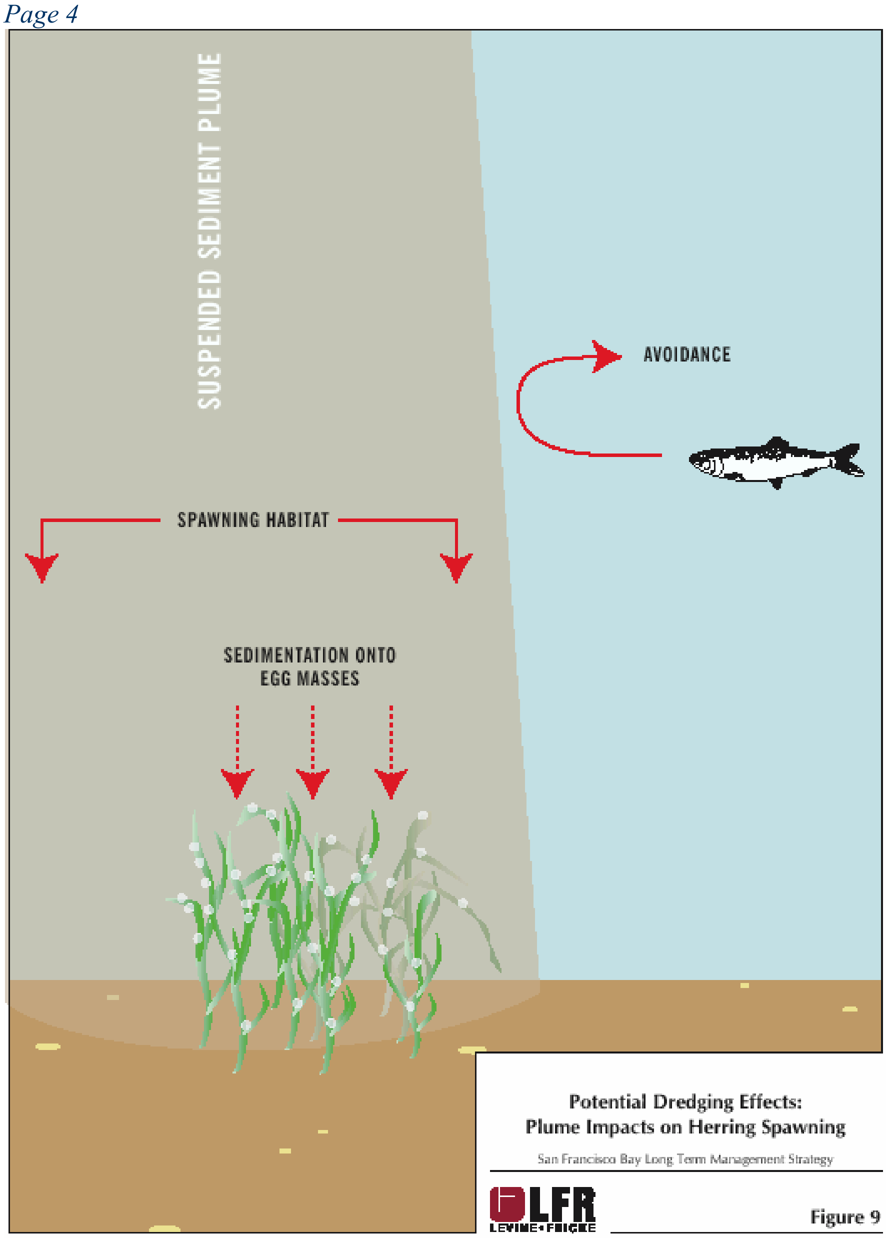

Figure 1-2. Possible effects of dredging operations on Pacific herring include avoidance by spawning adults and sedimentation onto egg masses (from LFR 2004)

This white paper examines the potential for effects of dredging operations on the San Francisco Bay herring population and recommends research that could further determine the efficacy and need for environmental work windows. The report presents information using two conceptual models:

- **Section 2, Factors that Affect Herring Populations**, which examines all factors that affect herring populations at each life stage.
- **Section 3, Possible Effects of Dredging,** which more specifically examines dredging operations and assesses their potential effect on the fish.

Section 2 examines all factors, both natural and anthropogenic, that potentially affect local herring populations. Section 3 examines the potential effects of dredging on local herring populations, including effects of suspended sediments, dissolved oxygen, contaminants, and noise. These topics overlap with the discussion in Section 2 but focus specifically on dredging activities. For example, Section 2 discusses possible effects of naturally occurring suspended sediments on herring, while Section 3 examines the potential effect of dredging-induced suspended sediments.

This white paper is the product of an expert panel, which met twice to review existing data and to suggest potential further research. Regulators, dredging permittees, the fishing community, and dredge operators also reviewed information and made recommendations. The panel's goal is not to definitively characterize impacts of dredging activities on San Francisco's Pacific herring population but to determine research needs and suggest areas for further study. These research needs and areas of possible study are presented in **Section 4, Conclusions**. The remainder of this introduction presents general information about Pacific herring and dredging activities in San Francisco Bay.

1.1 Pacific Herring in San Francisco Bay

The Pacific herring (*Clupea pallasii*) is a schooling species, found in nearshore and continental shelf waters on both sides of the North Pacific, from arctic waters, south the turbid Yellow Sea in Asia and to Baja California in North America (Figure 1-3). The largest populations of Pacific herring in North America occur in British Columbia and Alaska. San Francisco Bay supports the most southerly commercial fishery and the largest herring population in California (DFG 2001). Commercially harvested spawning populations also occur in Tomales Bay, Humboldt Bay, and Crescent City Harbor, California. These bays are colder and less turbid than San Francisco Bay.

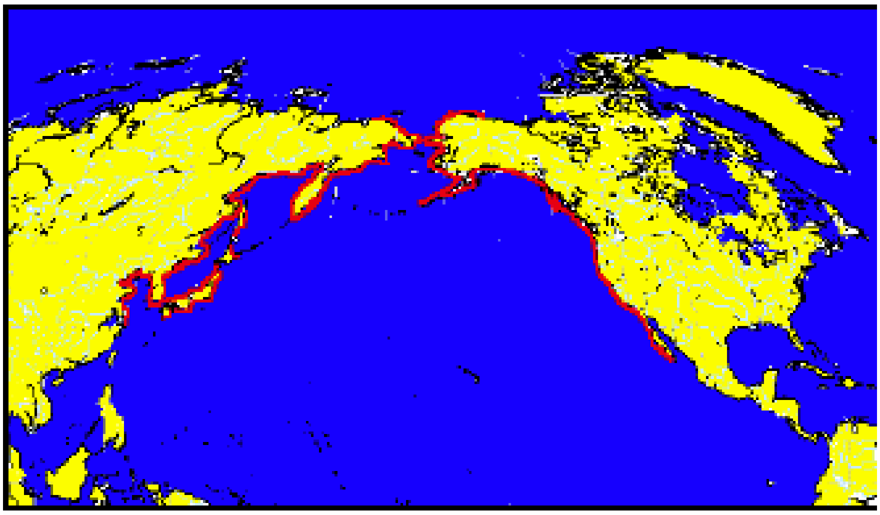

Figure 1-3. Distribution of Pacific herring (from SWRCB, www.swrcb.ca.gov)

Pacific herring spend much of their lives offshore, but they spawn annually in bays and estuaries. Little is known about their movements or behavior in offshore waters. Limited data enumerating herring caught by research programs targeting other species show general areas where herring have been caught but do not represent the entire range of the population (Figure 1-4).

California Pacific herring mature at two to three years of age. Mature fish enter nearshore waters days or weeks before spawning and spawn in a series of events, known as "waves," over several months. Herring spawning occurs from November though the end of March. December through February is the historical peak spawning time in San Francisco Bay (Watters *et al.* 2004), although DFG scientists have noted an increase in spawning events in March (DFG, personal communication), a trend that has also been noted in British Columbia (Doug Hay, personal communication). Herring spawn on eelgrass, seaweed, rock, pier pilings, retaining walls, rip-rap, and boat bottoms. Adult herring leave the Bay after spawning.

Consistently, each year, herring are observed to spawn in Richardson Bay, an embayment located between Sausalito and Tiburon in North Central Bay, but other San Francisco Bay spawning sites vary from year to year (Figure 1-5). During 1973-2001, most of the spawning activity has taken place in the North Central Bay, including Richardson Bay. Significant spawning has also occurred along the San Francisco waterfront (Watters *et al*. poster, available at www.dfg.ca.gov/Mrd/herring/poster.html).

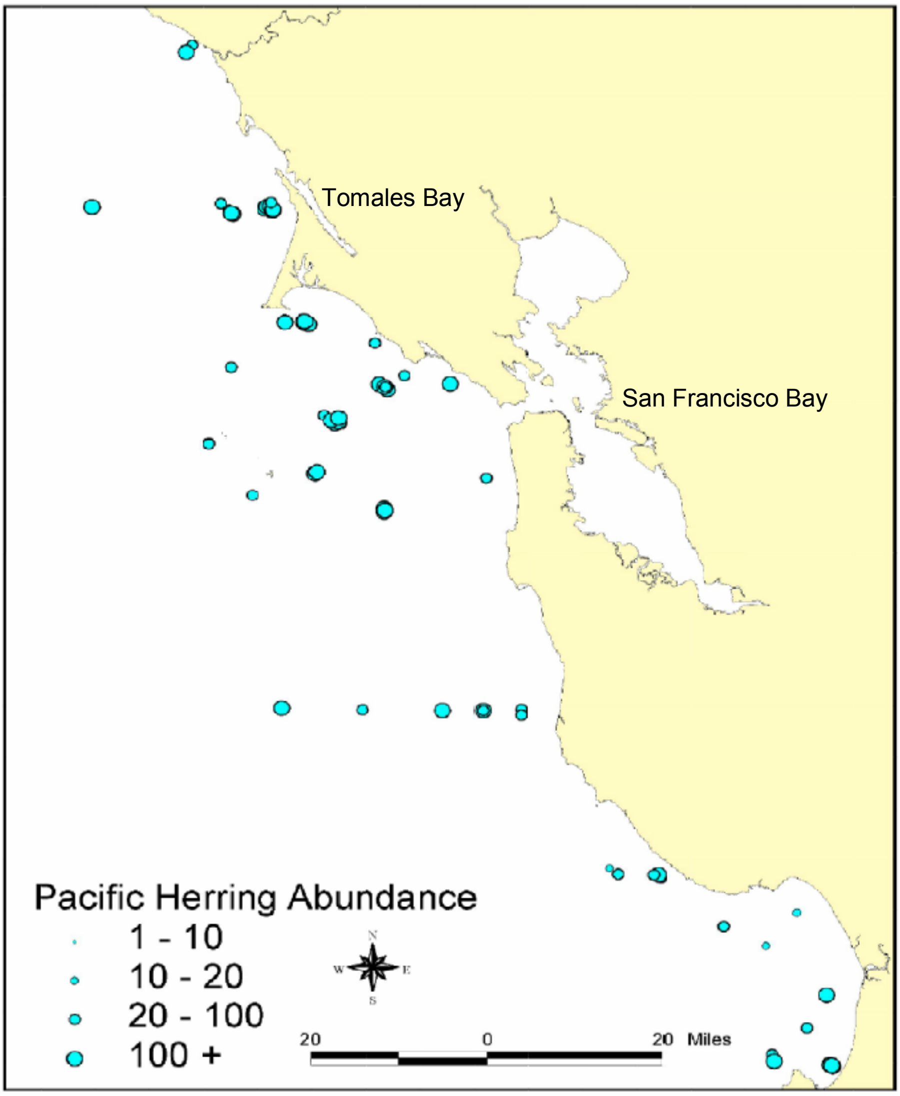

Figure 1-4. Pacific herring in California coastal waters 1983-2003 (from NMFS). (Note that the sampling program was not directed at Pacific herring; the data do not delineate total range or abundance of the species.)

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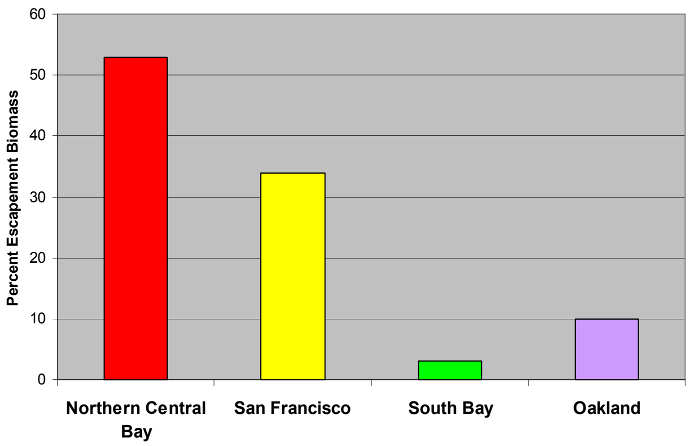

Figure 1-5. Historical herring spawning areas in San Francisco Bay and percent spawn escapement biomass by region (from DFG). Red=North Central Bay including Richardson Bay; Yellow=San Francisco; Green=South Bay; Purple=Oakland, extending to Richmond

DFG conducts annual surveys of herring spawning biomass (Figure 1-6). Low herring biomass in San Francisco Bay is typically associated with the years following El Niño events, presumably because lack of upwelling reduces food production and/or because the associated warm waters displace the herring to the north (Hay *et al.* 2001). El Niño years tend to produce smaller sized fish coming into the Bay (Tom Moore, DFG, personal communication).

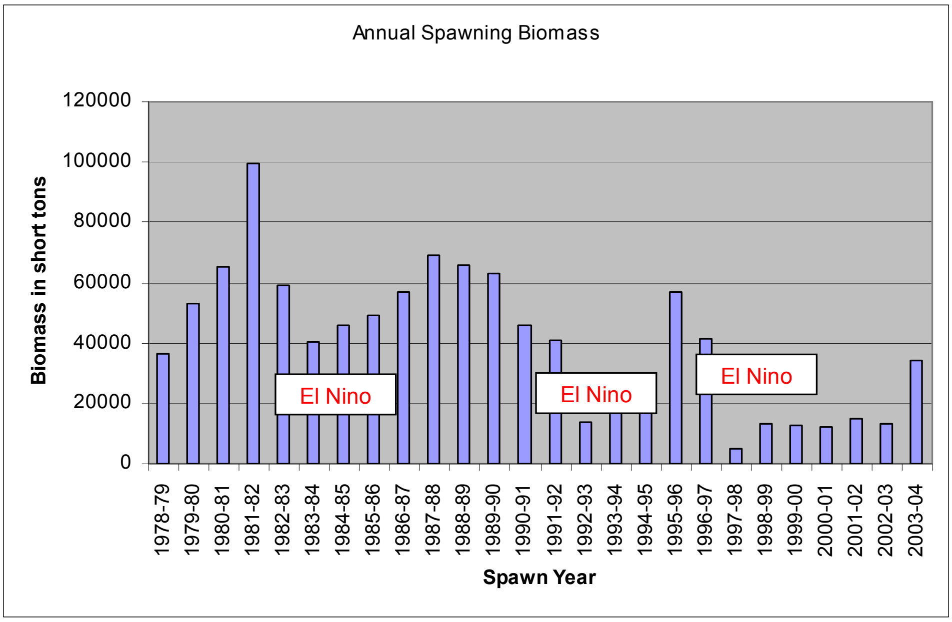

Figure 1-6. Annual spawning biomass based on spawn deposition surveys (from DFG)

Herring are deposit spawners, and their eggs are very sticky, coating the spawning substrates. Eggs hatch in about 8-10 days in San Francisco Bay (Vines *et al.* 2000). Larvae and juveniles remain in the Bay until fall. Distribution and abundance of larvae and juveniles have not been well studied by programs that target the species. Abundance data for juveniles are available from the monthly midwater trawls conducted as part of the DFG Central Valley Bay-Delta Branch San Francisco Bay Study (Figure 1-7). These midwater trawls are conducted at open water stations located from the most southerly portions of the Bay north into the Sacramento and San Joaquin rivers. During 2003, Age 0 Pacific herring were found in South, Central and San Pablo bays (Hieb *et al.* 2004). During May-September, herring were found predominantly in the Central Bay channels. By October, only a few dozen were fish caught in the midwater trawl.

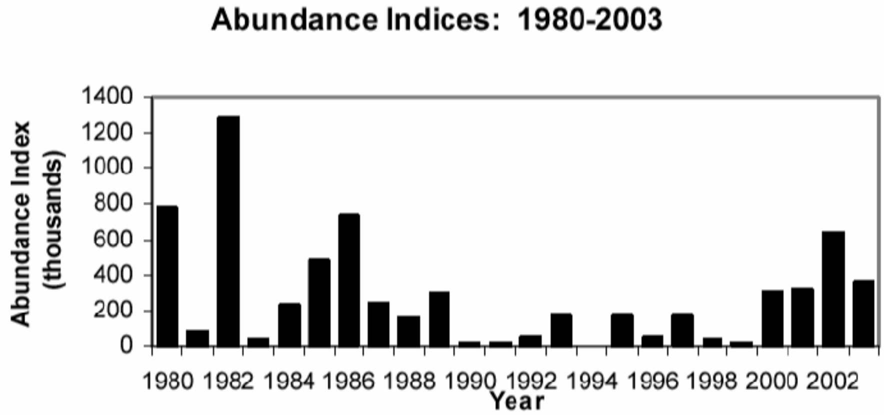

Figure 1-7. Annual young of the year index for Pacific herring from April-September midwater trawl (DFG 2004)

All life stages of herring feed primarily on zooplankton. Larvae eat primarily copepod eggs and nauplii and larval stages of other animals. Juveniles and adults feed on copepods and other zooplankton. Herring are prey to invertebrates, birds, fishes, and mammals.

The San Francisco Bay herring fishery (reviewed in Smith and Kato 1979, Spratt 1981, DFG 2001; Figure 1-8) has reflected changes in market demand. The fishery began in about 1850, and by the late 1800s, 35-40 boats fished, primarily in Richardson Bay, but also on the eastern side of the bay, south of Alameda and off Point Richmond. Most of the fish were sold fresh in local markets. Demand increased during World War I, and a local canning and reduction plant opened. Reduction to fish meal peaked in 1918. After the war, canning ceased, reduction was limited, and only small numbers of fish were landed for the fresh market, bait, and smoking. Catches rose after World War II, when there was a brief but unsuccessful attempt to substitute herring for the declining sardine stock. Those catches peaked in 1952.

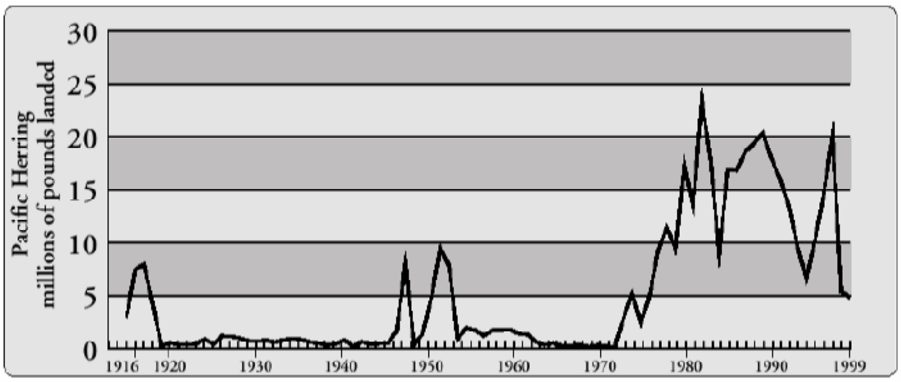

Figure 1-8. California Pacific herring landings (DFG 2001)

Catches remained very small through the 1960s, until a specialized fishery for herring roe developed following a crash in herring stocks in Japan and a Japanese-Soviet ban on fishing in the Sea of Okhotsk, a formerly large herring fishery located between Japan and Russia. There are three California herring fisheries. The largest fishery takes whole egg skeins, called *kazunoko,* from female fish that have been caught in anchored gill nets. Another fishery is for eggs deposited on kelp fronds (*Macrocystis* sp., harvested in Southern California), referred to as *kazunoko kombu* or eggs-on-kelp. A third, very small, fishery is for fresh fish.

The San Francisco Bay herring roe fishery began in January 1973. Catches of California herring have been variable and are about 10% of those in Alaska. During the first season, DFG realized that the population could easily be overfished, and emergency legislation was enacted to establish fishing limits. Since then, the fishery has been heavily regulated. The purse seine fishery was closed in the early 1990s, and all permittees converted to the use of gill nets. Allowable mesh size has changed twice (Table 1-1). In 2004, members of the herring fishing community requested a decrease in minimum allowable net mesh size to 2 inches (Liberati *et al*. 2004), but that change has not been approved.

Table 1-1. Changes in gill net mesh size in the Pacific herring fishery in San Francisco Bay

Period	Net Mesh Size (inches)	
	Minimum	Maximum
1976 to January 14, 1983	2	2.5
January 14 – December 31, 1983	2.25	2.5
January 2, 1984 – present	2.125	2.5

There are many potential impacts to Pacific herring in San Francisco Bay both natural and anthropogenic. Other Bay fisheries have suffered from the same stresses. At one time, there were fisheries for bivalves, shrimp, salmon, sturgeon, and other finfishes; by the 1970s, the only remaining fisheries were for herring, anchovy, and bay shrimp, and the latter two were used almost exclusively as bait (Smith and Kato 1979). The life stages within the Bay (egg, larva, juvenile) are susceptible to predation, a turbid environment, contaminants, habitat degradation, noise, changes in environmental conditions, fishing pressure, and other human activities, including dredging.

1.2 Dredging in San Francisco Bay

Large-scale dredging has taken place in San Francisco Bay for more than 100 years (LTMS 1998). USACE maintains 17 deep- and shallow-draft channels in the Bay, and smaller channels, marinas, and berthing areas are maintained by private organizations (Figure 1-9; Table 1-2). Maintenance dredging involves removal of recently deposited sediments while removal of sediments in their natural condition is considered new work construction (LTMS EIS/EIR 1996). Dredging at maintenance sites occurs with varying frequency and intensity.

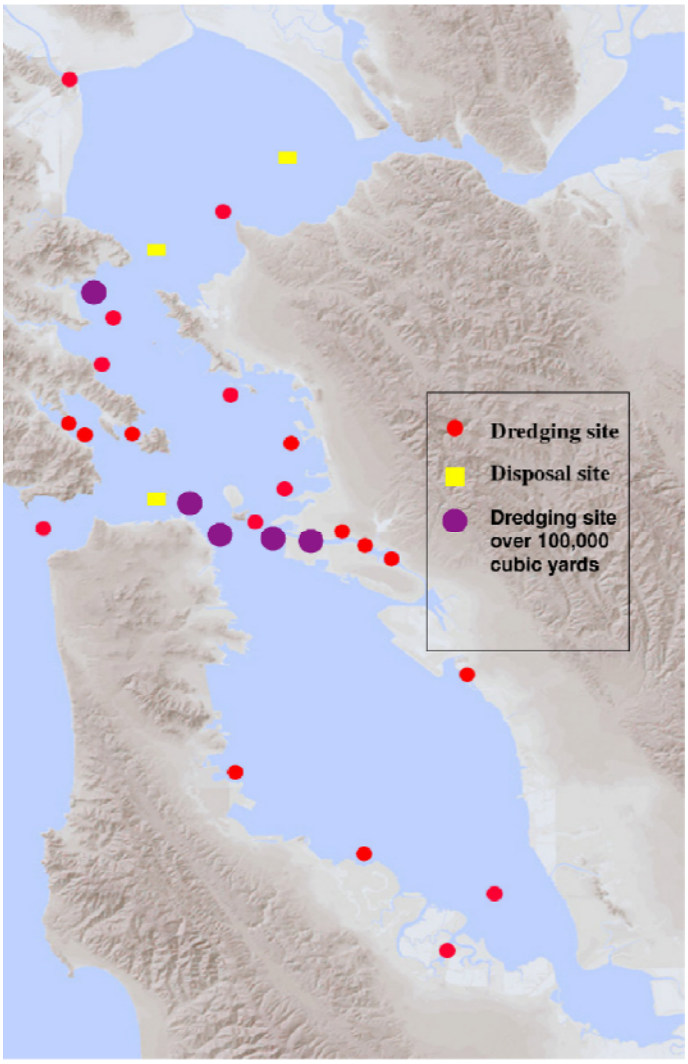

Figure 1-9. Some dredging locations and disposal sites in San Francisco Bay

Table 1-2. Dredging volume estimates for 1995-2045 (from LTMS EIS/EIR)

Quantity Type	***Low Range Estimate (cubic yards/year)***	***Mid Range Estimate (cubic yards/year)***	***High Range Estimate (cubic yards/year)***
Historic maintenance and new work (1)	6,840,213	6,840,213	6,840,213
Removal of historic new work (1)	-393,062 (-100 percent of all new work)	-284,116 (-50 percent of selected new work)	-155,170 (-0 percent of selected new work)
Estimated range of historic maintenance dredging	6,447,151	6,556,097	6,685,043
Removal of dedicated disposal sites and base closures (2)	-3,223,662	-2,478,111	-1,720,195
Projected maintenance dredging	3,223,489	4,077,986	4,964,848
Addition of projected new work dredging (3)	242,000 (+50 percent)	484,000 (+100 percent)	968,000 (+200 percent)
Total	**3,465,489**	**4,561,986**	**5,932,848**
Rounded total	**3,470,000**	**4,560,000**	**5,930,000**
50-Year Projected Total Dredge Material Volume	**173,500,000**	**228,000,000**	**296,500,000**

Notes: (1) For projects with separable new work quantities, the entire quantity was deleted in all estimate ranges. For records without separable quantities, 100 percent, 50 percent, and 0 percent of the entire annual reported volume was removed for the low, mid, and high range estimates, respectively (see Table 3 in Appendix E).

(2) For projects with dedicated disposal sites, and military base closures, 100 percent, 50 percent, and 0 percent of the quantities were removed with the exception of the San Francisco Bar, which was entirely removed (ocean disposal only), and the Mare Island Straits, which had 50 percent, 25 percent, and 0 percent removed since it is known that this dredging will not cease entirely with the closure of Mare Island Naval Shipyard (see Table 3 in Appendix E).

(3) See Table 4 in Appendix E, and subsequent paragraphs.

There are two major types of dredging equipment (Figure 1-10):

- **Hydraulic dredges**, including cutterheads, dustpans, hoppers, hydraulic pipelines, plain suction, and sidecasters. Hydraulic dredges remove material in slurries and are generally used for maintenance projects. Hydraulic dredges are generally faster than mechanical dredges and create less resuspension of sediments than mechanical dredges.
- **Mechanical dredges**, including clamshell, dipper, and ladder dredges. Mechanical dredges remove material through direct force and are used both for new and maintenance projects. Mechanical dredges cause more sediment resuspension when dredging occurs in fine, loose or non-cohesive substrate.

Although hydraulic dredges cause less disturbance and resuspension of sediments, hydraulic dredging entrains considerable water from the dredging site. Equipment type varies by project. Smaller, shallower dredging projects use different equipment than deep water dredging projects and therefore data can not be compared between them.

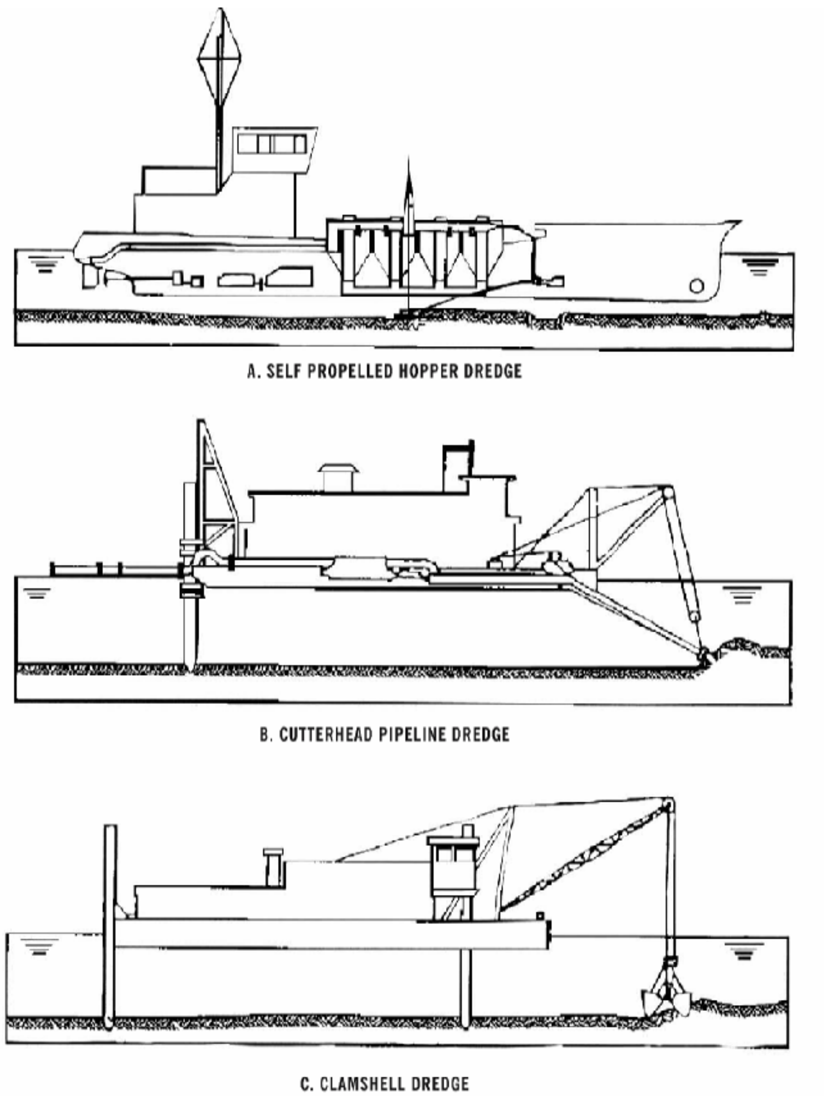

Figure 1-10. Dredge types (from USEPA and USACE 1992)

2. Factors that Affect Herring Populations

Clupeid fishes, including Pacific herring, are generally subject to great fluctuations in abundance over short- and long-term cycles. Many factors affect herring production (Lasker 1985), and understanding the potential effects of dredging on the population requires putting the possible effects into the context of all the factors that may affect the stock. A simple conceptual model of the life cycle of herring and potential impacts at various life stages is presented in Figure 2-1.

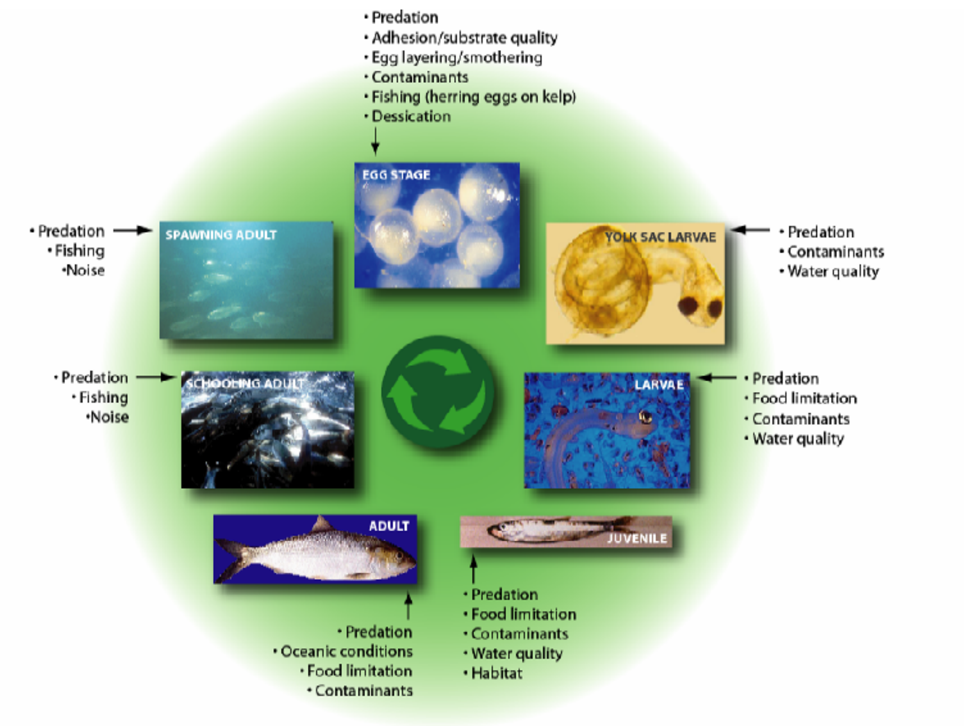

Figure 2-1. Potential factors affecting Pacific herring

Pacific herring inhabit San Francisco Bay during most life stages. Adult herring enter the Bay to spawn, generally remaining for days or weeks after spawning and before leaving again for open waters. Juveniles leave for the open ocean during the fall and mature into adults in the open ocean (Hieb *et al.* 2004). The conceptual model depicts the many factors that affect the herring population both in the Bay and at sea.

Natural factors that may affect herring populations include direct temperature effects, salinity, other water quality factors, competition for food, predation (by invertebrates, birds, mammals, and fishes), disease, and egg smothering (by other eggs and sediments). Human-based factors include fishing, habitat loss, contaminants from municipal wastes, industrial effluents, noise (for example from pile driving, vessel traffic, or dredging operations), and sedimentation.

Mortality of fishes is typically greatest during the first year of life, and Norcross and Brown (2001) estimated survival for each early life stage of Pacific herring in Prince William Sound, Alaska:

- Eggs: 24-45% survival, with wave action being the biggest source of mortality. Predation and smothering by dense egg deposits were also factors.
- The post-hatch: 50-100% survival, with warm water causing contorted bodies and reduced jaw size, which could lead to starvation.
- Larvae: model results indicated 7% survival to July 1 and 1% survival to August 1, when the larvae metamorphosed to juveniles. Starvation and predation were the major causes of mortality.
- Autumn juveniles: 2-15% survival, with the mechanism of mortality not defined.
- Winter juveniles: 4-99% survival, depending upon conditions within the individual bays in which the juveniles overwintered.

Similar estimates have not been made for California fish. Eggs and larvae are assumed to be the most sensitive of life stages but relatively little is known about habitat quality, distribution, and the factors that affect larvae. For many species, successful recruitment may be influenced more by the success of the larval and juvenile stages than the egg stage (Jeep Rice, personal communication). For San Francisco Bay herring, year class strength is not predicted by herring egg biomass estimates but is dependent on egg or larval survival through the juvenile stage (O'Farrell and Larson 2005).

Stock collapse has occurred in Pacific and Atlantic herring populations and is often thought to be caused by multiple factors. For example, Carls *et al.* (2002) built a case that high population size, disease, and suboptimal nutrition led to stock collapse in Prince William Sound, Alaska in the early 1990s. Fishing and environmental change are frequently cited as a causes of herring stock collapses. Other factors include changes in food supply, predation, pollution, and habitat modification.

2.1 Effects of Fishing

There is considerable evidence that fishing can affect herring stocks. For example, Hay and Kronland (1987) found a significant reduction in spawning biomass with increased catch in the Strait of Georgia, British Columbia. Hay *et al.* (2001) reviewed the histories of herring stocks in the Atlantic, Pacific, and Arctic oceans and found that fishing was a major factor in stock declines. Most stocks rebound following periods of low biomass, but an exception was the once-great Hokkaido-Sakhalin stock in Asia, which collapsed in the first half of the last century and has remained low for more than 50 years, perhaps having been fished to the point of "functional extinction."

DFG heavily regulates the herring fishery. The commercial herring fishery in California is one of the few fisheries to undergo annual population assessments and subsequent regulatory change. To avoid overfishing the stock, a model developed by the Pacific Fishery Management Council suggests that no more than 20% of the total population should be taken each year. Doug Hay (personal communication) suggests that 20% removal may be acceptable only if it applies to all forms of anthropogenic loss, not just to fishing. The 20% target applies only to the population above a benchmark estimate of the spawning stock biomass necessary to regenerate the population. If biomass estimates fall below that benchmark, then there should be no allowable fishing quotas established for that year. As a conservative approach, DFG calculates quotas based on 20% of the spawning population rather than the total (Diana Watters, DFG, personal communication).

DFG originally calculated quotas from data collected during spawn deposition surveys. During the mid-1980s, DFG experimented with hydroacoustic surveys to augment the spawn deposition survey data, and began to use them as independent estimates of stock size for the 1989-1990 spawning year. However, DFG noted and became concerned about increasingly divergent results yielded by the two methods. Consequently, in 2003, a review of herring population assessments was conducted by a California Sea Grant panel. The review determined that the hydroacoustic method overestimated biomass and that its use during 1989-2002 resulted in inflated target exploitation rates for those years (McCall *et al.* 2003). The review suggested that in some years, actual exploitation rates may have been about 40% of the spawning population, suggesting much greater fishing pressure than had been planned. Some fishermen disputed that figure, suggesting that personnel changes at DFG resulted in inconsistent and underestimated spawn deposition (E. Koepf, personal communication). DFG recommended closing the herring fishery for the 2003-2004 season, however, the state Fish and Game Commission adopted a less restrictive strategy, which included a reduced quota and a shorter fishing season.

Information about spawning stock size suggests that herring stock is low, and potential effects on the population, including those from fishing, may be greatest when absolute numbers are low. Numerous research needs are ongoing. For example, there remain questions about the best methods of determining spawning biomass, and there has been limited discussion of potential effects of fishing practices on the geography and temporal progression of the spawning season and the age structure of the population.

2.2 Effects of Environmental Factors

DFG has noted that herring populations in San Francisco Bay are typically lower in the years following El Niño events, and the effects of water temperature, salinity, and other water quality parameters on herring populations have been evident for a long time (*e.g.*, Hay *et al.* 2001).

Watanabe *et al.* (2001) suggested that in comparison to other clupeid fishes, Pacific herring may be especially likely to be affected by temperature and other environmental factors such as nutrient availability. Most Pacific herring continue spawning for 4-5 years after maturation, a long life span, which may increase the chance of an individual fish spawning at least once in favorable oceanic conditions.

One possible effect of El Niño years on herring populations in San Francisco Bay is that warm temperatures displace fish northwards. Research has suggested that optimal temperatures for fertilization and hatching are lower than those that occur in San Francisco Bay. Similarly, on the other side of the Pacific, Ivshina (2001) found that the Sakhalin-Hokkaido spawning grounds decreased first in the southern part of the range and suggested sea warming as the cause.

Laboratory and field studies of more northern herring have found optimum temperatures for hatch, size at hatching, and survival to the post yolk-sac stage to be about 3-9°C (Alderdice and Velson 1971, McGurk 1984), lower than temperatures typically found in San Francisco Bay (Figure 2-2). Using typical temperatures for the Bay, Cherr and Pillai (1994) found that hatching rates were better at 12°C than at 15°C, and Griffin *et al.* (2004) noted that the spawning period corresponded to the lowest temperatures in the Bay.

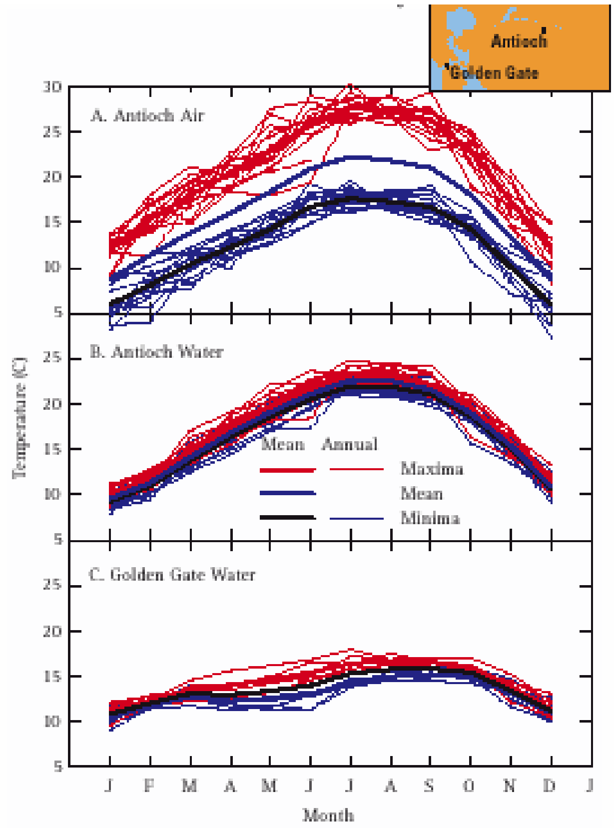

Figure 2-2. Water temperatures in San Francisco Bay (Kimmerer 2004)

On the population level, Hay and Kronland (1987) found that both sea-surface temperature and spawn deposition in the Strait of Georgia, British Columbia, exhibited three cycles from the 1930s to the mid 1980s. A lag of four years provided the strongest negative correlation between temperature and subsequent spawning. Wespestad and Gunderson (1991) found that time of spawning in the Bering Sea was correlated with temperature; however, spawning success appeared to have little effect on recruitment, as measured by the catch. Similarly, spawning success shows no correlation with subsequent catch in San Francisco Bay data.

Optimum salinity for eggs and larvae ranges from about 10 to 17‰ in northern fish (McMynn and Hoar 1953, Alderdice and Velson 1971, Alderdice and Hourston 1985). Using San Francisco ranges, Cherr and Pillai (1994) found optimal fertilization and hatching success at 16-20‰, with fertilization and hatching rates decreasing at salinities above 24‰. Hatching rates were better if temperature was lower (12 *vs.*15°C), particularly at higher salinity.

Field data compiled for San Francisco Bay indicate that spawning occurs when temperature and salinity are at their lowest. Fertilization, development, and larval survival occur at 3-22°C and 2-35‰ throughout the range of the species (Griffin *et al.* 2004). Optimum conditions for fertilization and development of San Francisco Bay herring were 12-24‰ at 12°C. Yolk-sac larval survival was higher in experiments with salinities of 4 and 16‰ (>68%) than at 32‰ (0-31%). Larvae raised through embryonic development in 4 and 16‰ had significantly higher mortality when moved to salinity of 32‰ than those moved to salinities of 4 or 16‰. Larvae from early spawns (January and February) tolerated high salinity, and those from later spawns (March) tolerated low salinity.

Salinity levels in San Francisco Bay are dependant on the amount of outflow from the Sacramento-San Joaquin Delta, which is variable from year to year (Figure 2-3). In low outflow years, X2 (a measure of the horizontal distance from the Golden Gate Bridge to the point where tidally averaged near-bottom salinity is 2‰) can be up to 90 km, whereas during years of high outflow, X2 can be less than 50 km (Kimmerer 2002). There is a weak positive correlation between the herring young-of-year index and Delta outflow (Figure 2-4). High delta outflow can reduce salinity levels and move the position of X2 further seaward. High outflow can also increase turbidity in the Bay (Figure 2-12, Table 2-2). Reduced salinities and increased turbidity do not correlate well with the young-of-year index.

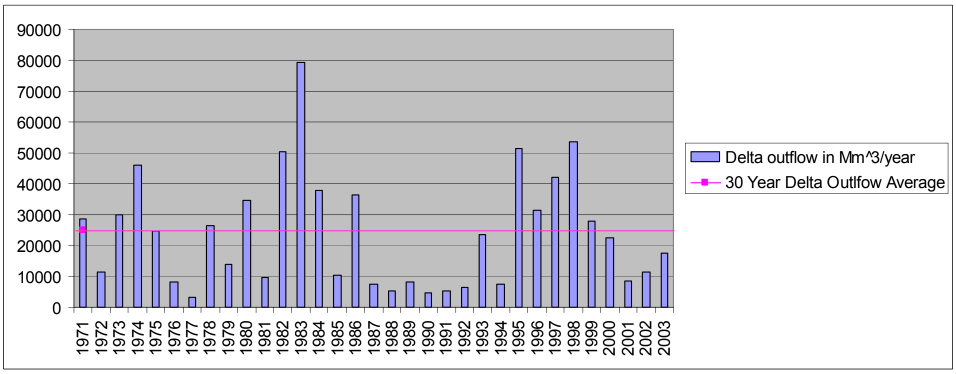

Figure 2-3. San Joaquin/Sacramento River Delta annual outflow by water year

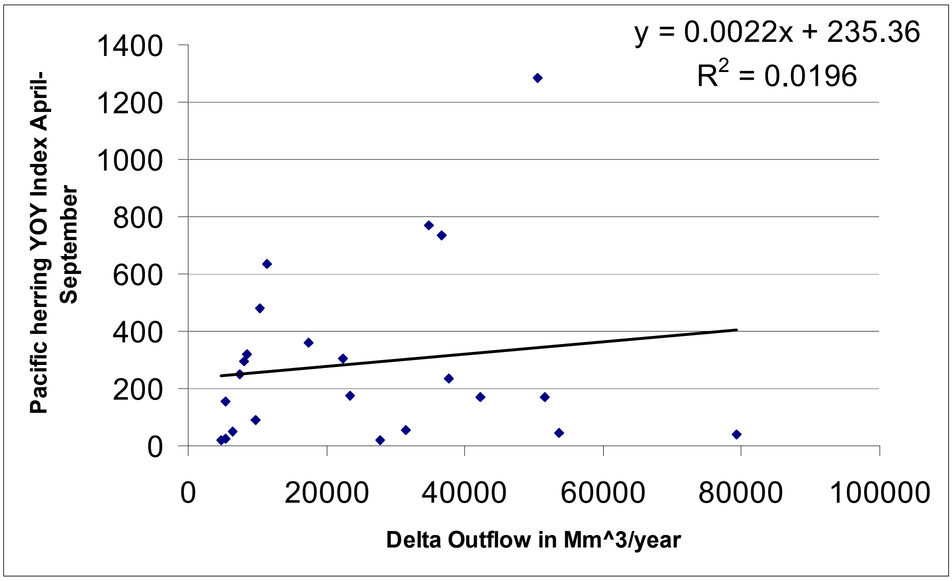

Figure 2-4. Pacific herring young-of-year index and Delta outflow data show a weak, positive correlation

There has been considerable research on the relation between herring populations and decadal-scale climate indices (*e.g.*, Ware 1991, Brown 2002, Landis *et al.* 2003). For example, trends in abundance of northern Gulf of Alaska Pacific herring stocks have been in phase with several decadal-scale climate indices. High population levels corresponded to intensification of the Aleutian Low (which provided good conditions for primary and secondary productivity), higher sea-surface temperatures, and increased storms. Warmer sea-surface temperatures associated with the Pacific Decadal Oscillation were identified as a major factor in herring declines at Cherry Point, Washington.

Mysak (1986) and Mysak *et al.* (1982) found a strong correlation between high salinity and high herring recruitment off Vancouver Island, with both factors varying in 6-year cycles. High salinity and an increased upwelling of nutrients to surface waters may result from stormy winters (high wind wave mixing induces upwelling) that often occur during El Niño years. Springs following stormy winters therefore have more nutrients, which promote a longer phytoplankton bloom, which in turn increase food sources. Strong year classes for herring in Alaska waters also coincided with strong El Niño Southern Oscillation (ENSO) events.

In preparing this white paper, we compared spawn survey biomass and young-of-the-year indices for San Francisco with temperature and salinity data and two climate indices, the California Upwelling Index and the California Multivariate ENSO Index. The limited data for comparison show positive correlations between annual spawning biomass and temperature at 0 and 4-10 year time lags and biomass and salinity at 0-4 year time lags. There were negative correlations at time lags of 4-9 years for temperature and 5-10 years for salinity. Preliminary comparisons of annual spawning biomass and the California Upwelling Index indicated negative correlations at time lags of 0-5 years.

Investigation of the effects of environmental factors on the San Francisco Bay herring population could form the basis for a variety of research efforts. No information on temperature and salinity within spawning areas and throughout spawning seasons has been synthesized. The relative effects of conditions in the Bay during spawning and for larvae and juveniles as compared to the effects of broader ocean conditions on the adult population are not known. Populations of other ocean fish, such as hake, sardines, and anchovy, have been more extensively studied and may provide examples for herring investigations.

2.3 Effects of Food Resources and Competition

Food resources and competition for food are much-discussed topics in marine ecology of fishes, particularly for larval stages, but also for juveniles and adults. Many papers cite the Hjort (1914) theory of a critical period for marine fish larvae, that is, that insufficient food during the time of first feeding is a major factor in determining year-class strength. Adult fish may also be affected by food levels. One theory about the effects of El Niño on Pacific herring populations is that the lack of upwelling reduces food production, a factor that would primarily affect adult fish on the continental shelf.

Yields of fish and shellfish from freshwater and marine systems are typically greater in areas with greater primary production, and San Francisco Bay is not as productive as many other coastal embayments, including Tomales Bay (Figure 2-5). Throughout the estuary, phytoplankton growth rates tend to be limited by light (Kimmerer 2004). North San Francisco Bay is less productive than South San Francisco Bay.

In a master's thesis, Gartside (1995) attributed a measurable difference in larval herring growth to the lower productivity in North San Francisco Bay compared to South San Francisco Bay. She collected herring and copepod life stages from stations north and south of the Bay Bridge. There were more herring larvae north of the bridge, but larger, faster growing individuals at the southern stations. There were also more copepod nauplii south of the bridge, which she attributed to lower turbidity and higher annual productivity.

There are other possible explanations to Gartside's data, and her conclusions may be contradicted by Bollens and Sanders (2004) who found that herring larvae from the more northerly San Pablo Bay (north of spawning locations) were more abundant and larger than same-age larvae from the Central Bay. They examined the diets of herring larvae in greater detail than did Gartside, and found that in the Central Bay, the larvae fed less on copepodids (young copepods), copepod nauplii, diatoms, sediment, and gastropod veligers and more on tintinnids (very small ciliates). Larvae from a tidal marsh near China Camp (on the Marin peninsula, north of the Richmond-San Raphael Bridge) in February had a higher proportion of larger prey items, although tintinnids remained a significant part of the diet. Condition of the larvae suggested that tintinnids were an adequate diet.

Food limitation does not appear to be a major factor affecting herring larvae in the productive northern waters of British Columbia and Alaska (McGurk 1984, 1989, McGurk *et al.* 1993). There has also been no evidence of competition for food between herring larvae and likely competitors, such as soft-bodied jellies (Purcell 1990, Purcell and Grover 1990). Nowhere did grazing by jellies remove more than a small amount of the daily production of prey.

There is, however, some evidence of food limitation for juvenile herring (Foy and Norcross 1999a, 1999b, Norcross *et al.* 2001, Brown and Norcross 2001). Feeding during the summer and fall appeared to be critical for juvenile survival through the winters in Prince William Sound. Zooplankton density at the time that herring were becoming Age 1 and still rearing in nursery bays corresponded to adult abundance at Ages 3 and 4.

The more stable seasons but overall lower productivity in San Francisco Bay may make for differences from the more northern populations. Kimmerer (personal communication) has found that zooplankton abundance in San Pablo, Central, and South San Francisco bays is generally less than that found in other United States estuaries, and populations of many species have declined in recent decades.

Introduction of exotic zooplankton species has also been a concern for San Francisco Bay (Figure 2-6). Those species have been smaller than the native species they have replaced and may be less suitable food for juvenile herring. Most studies of exotic zooplankton have focused on Suisun Bay (more northerly than the part of San Francisco Bay used as a herring nursery), where average weight of individual zooplankters decreased by 80% from 1974 to 2003 (DFG data).

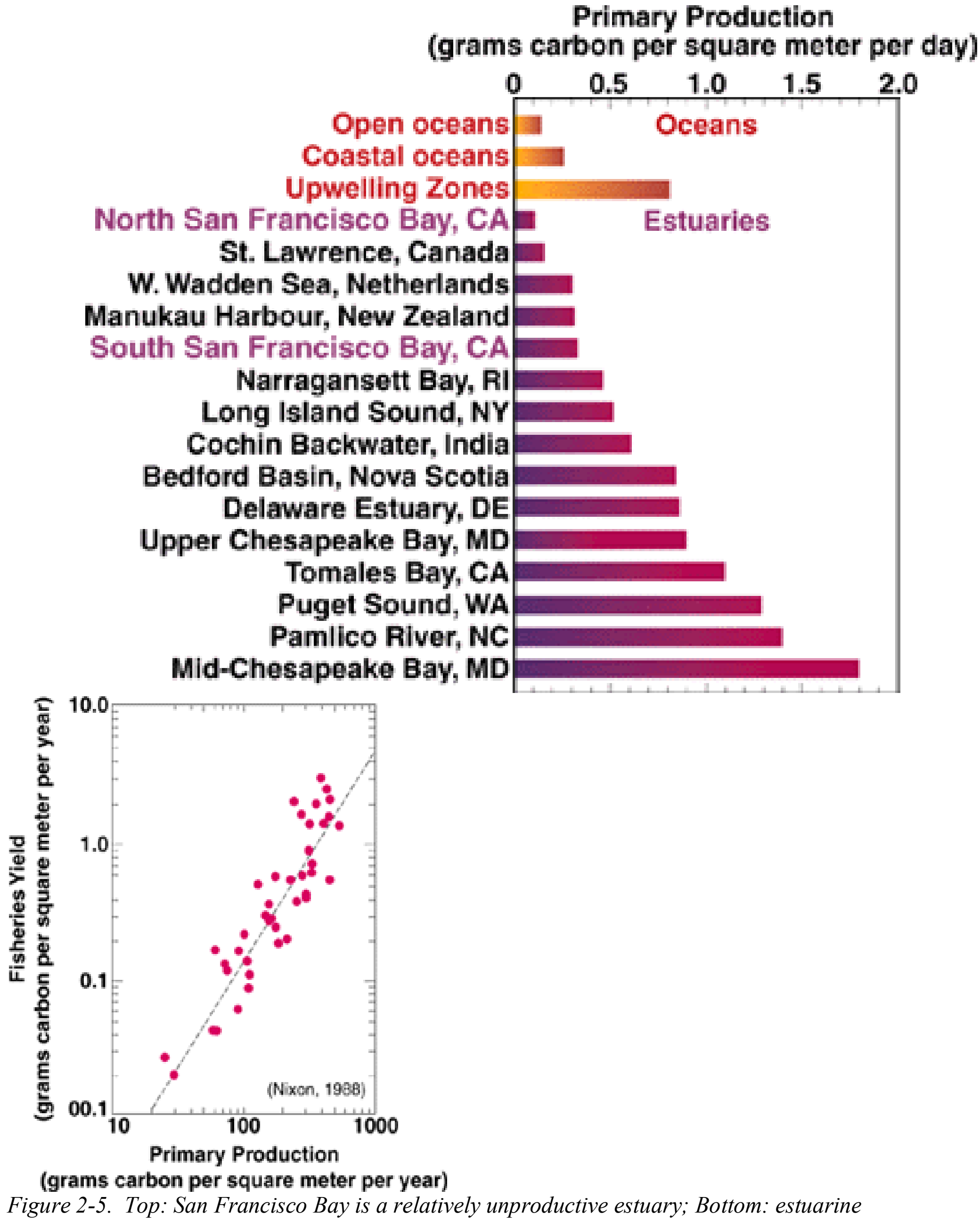

Figure 2-5. Top: San Francisco Bay is a relatively unproductive estuary; Bottom: estuarine fisheries yields are correlated with primary production (B. Cole and J. Cloern, USGS)

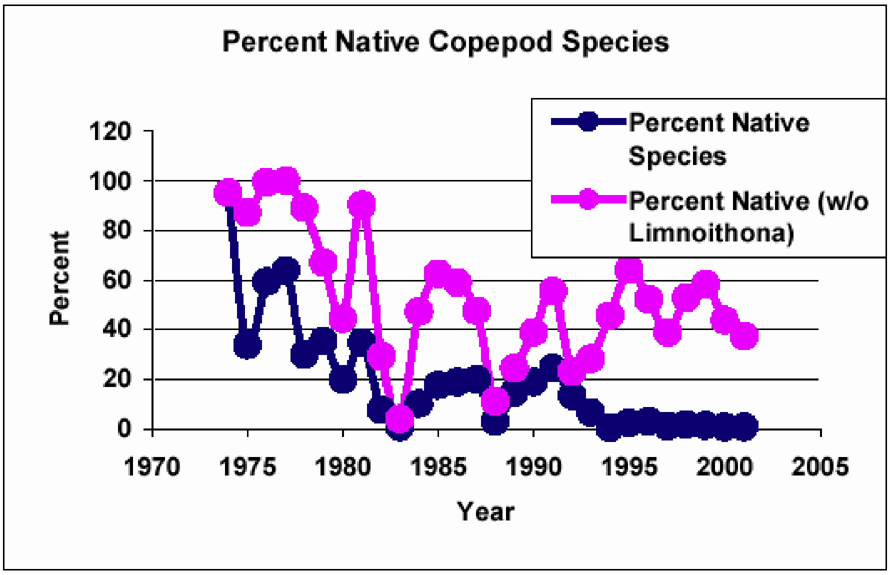

Figure 2-6. Decline of native zooplankton species in Suisun Bay (The Bay Institute 2003) (Limnoithona is a small copepod, introduced from China in 1979.)

Pacific herring in San Francisco Bay may currently be limited by food resources and by changes in the zooplankton community. However, little investigation has focused on food availability in herring spawning areas and nursery grounds. Better spatial and temporal information is necessary to relate these conditions to possible effects of dredging on Pacific herring.

Further, it is predicted that the large-scale restoration of salt marshes planned for South San Francisco Bay will increase light penetration throughout the Bay, and phytoplankton productivity could be increased. USGS has modeled the effects of South Bay salt pond restoration (Shellenbarger *et al.*2004).

2.4 Effects of Predation

At every life stage, Pacific herring are fed upon by a variety of predatory invertebrates, fish, birds, and mammals. Herring eggs are eaten by many birds, including gulls, diving ducks, geese, and crows, and by fishes. Larvae are consumed by other zooplankters, including gelatinous medusae, ctenophores, and other animals, collectively known as jellies. Juveniles and adults are significant forage for fish and marine mammals.

Predation on eggs. Although herring eggs are eaten by many predators, some field estimates of the effects on populations have indicated that egg predation is not a major source of mortality (*e.g.*, Haegele and Schweigert 1991, Haegele

1993). However, predation on eggs may be especially important when spawning biomass is low. For example, Haegele (1993) estimated that birds consumed less than 4% of herring eggs deposited in the Lambert Channel in the Strait of Georgia in 1989 and 1990, but he cited Palsson (1984) (a master's thesis) as having measured 95-99% consumption of a light spawn in Puget Sound.

Predation on larvae. Herring larvae may be especially susceptible to predation by jellies. Predation of herring larvae by jellies has been noted in the laboratory (Arai and Hay 1982) and Möller (1984) found a negative correlation between number of Atlantic herring larvae and biomass of the jelly *Aurelia aurita* in Kiel Fjord in Germany.

There is considerable evidence of predation of herring larvae by jellies in British Columbia (Purcell *et al.* 1987, Purcell 1990, Purcell and Grover 1990). Small species had little effect on herring larvae, but large species could significantly affect populations. One species of large hydromedusa *Aequorea victoria* consumed an average of 57% of the herring larvae per day and as much as 97% of the herring larvae present at one station. Abundance of the hydromedusa varied by two orders of magnitude between years and could have significantly affected herring recruitment.

Whether predation by jellies on herring larvae in San Francisco Bay is a factor that significantly affects recruitment is not known. Kimmerer (2002) noted that large jellies are frequently taken in San Francisco Bay and that smaller medusae, ctenophores, and chaetognaths are occasionally common. DFG has noted an increase in ctenophores, which have been observed to consume herring larvae, since the 1997-1998 El Niño (Eric Larson, DFG, personal communication).

Predation on juveniles and adults. Fish are important predators of herring juveniles and adults. The Pacific hake (*Merluccius productus*) is a species of special interest, because it competes with herring for food in its early years and then shifts to being a predator. The relationship between the species can be complex: McFarlane *et al.* (2001) found that when oceanic temperatures warmed off the west coast of Vancouver Island the abundance of the northern migration of Pacific hake increased. Herring, which made up approximately 37% of the hake diet, subsequently decreased in abundance. During this same period, waters in the Strait of Georgia were also warmer and hake biomass was high. However average hake length and weight decreased over the period in the Strait of Georgia resulting in a shift in hake diet from herring to euphausiids. Subsequently herring abundance increased because herring were eliminated from the diet of the hake.

Ware (1991) found that herring recruitment was negatively correlated with hake biomass in waters off Vancouver Island, noting that hake year-class strength tends to be higher than average when waters are warm in the Southern California nursery. DFG (2001) noted that hake stocks reached a historic high in 1987, about the same time that San Francisco herring stocks began their decline.

Another important predator is the Pacific harbor seal (*Phoca vitulina richardii*), found in and outside of San Francisco Bay (reviewed in Grigg 2003). Systematic population surveys of harbor seals began in the early 1970s, during which a seasonal influx of harbor seals corresponded to the winter herring run. Strawberry Spit, in Richardson Bay, was one of the more popular haul-out sites for harbor seals until around 1983, when anthropogenic disruption and a movement of herring out of Richardson Bay presumably resulted in seals leaving the area (Fancher 1987, Allen 1991 as reviewed by Grigg 2003). Yerba Buena Island has been more heavily used by harbor seals since the late 1990s (Kopec and Harvey 1995, Spencer 1997, Galloway 2000, Green *et al.* 2002 as reviewed by Grigg 2003). Within the Bay, the harbor seal population appears to be experiencing little change or a slight increase over time; considerable variability and time gaps make the data inconclusive. There is evidence of an increase in coastal harbor seals (Figure 2-7), however the increase is not at a level that is likely to be significant to the Pacific herring. In comparison, in the Strait of Georgia, British Columbia, population densities of seals are about two orders of magnitude greater than that found in San Francisco Bay (Doug Hay, personal communication).

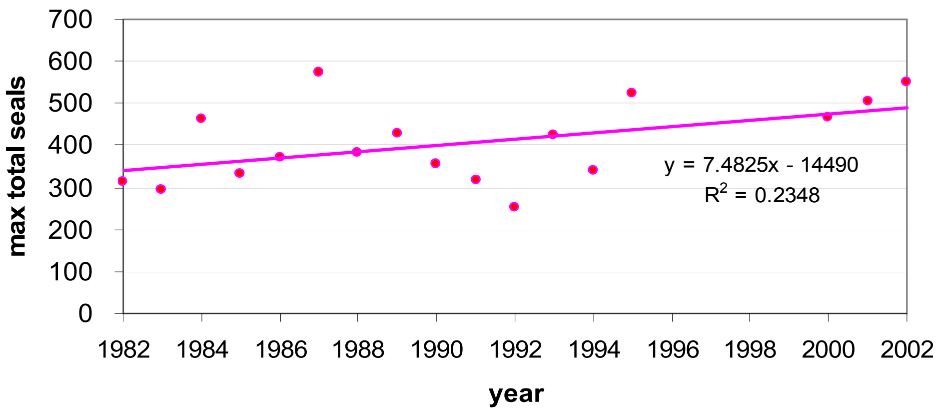

Figure 2-7. California harbor seal population (DFG aerial surveys)

Huber (1991) noted that peak numbers of sea lions coincided with winter herring spawning in Tomales Bay. California sea lion populations, which also consume herring, have increased an average of 5 to 8% per year since the passage of the Marine Mammal Protection Act in 1972 (US Dept. of Commerce 1999). DFG estimates that the California sea lion population is growing at a rate of 6.2 % per year (DFG 2001). No studies of the effects of harbor seal and sea lion predation on herring populations have been conducted.

2.5 Effects of Habitat

Spawning habitat. Successful herring spawning habitat is determined by vegetation type and slope of the beach (Haegele and Schweigert 1985, Alderdice and Hourston 1985). Hoshikawa *et al.* (2001) found that kelp was the dominant vegetation in a northern Japan bay, but that eggs were more often found on sea grasses. Vines *et al.* 2000 noted that in urbanized estuaries such as San Francisco Bay, natural spawning substrates have declined, and man-made structures, such as creosoted pilings, are used. Other herring spawning substrates include rocky and sandy shorelines and vegetation within these areas, rip-rap, pier pilings, concrete sea walls, and boat hulls (Spratt 1981, Watters *et al.* 2004). In the north Central Bay, including Richardson Bay, the predominant spawning vegetation is eelgrass and red algae *Gracilaria* spp. (Watters *et al.* 2004).

While herring spawn on a variety of substrates in the Bay, eelgrass beds and *Gracilaria* may be higher quality spawning habitat than man-made structures, and spawning may be more successful there. In Tomales Bay, herring spawn primarily on eelgrass beds (and also on *Gracilaria*), and DFG considers the extent of eelgrass habitat sufficient to support the spawning population (Tom Moore and Ryan Watanabe, DFG, personal communication). The extent of eelgrass beds is limited in San Francisco Bay: of the approximately 250,000 acres of open water in the bay, less than 3,000 acres or about 1% has eelgrass (compared to about 1,000 acres or 13% in Tomales Bay, (Figure 2-8; Merkel & Associates 2004). The second largest bed in the Bay and the one most stable through time, determined by low clonal diversity, is Richardson Bay, a consistent herring spawning area. The densest part of that bed is on the western side of the embayment, in the vicinity of boat moorings and marinas, at depths of 0.5-3.0 meters below mean low water.

The extent of eelgrass beds in San Francisco Bay may be reduced in comparison to historic levels, and the density and abundance of the existing beds is quite variable, indicating that the beds are stressed (Merkel & Associates 2004). Low light levels may be the factor that most limits the extent of growth. The largest beds are present in the Central Bay, which has the clearest water of any region of the Bay, and off Point San Pablo, which is also well-flushed.

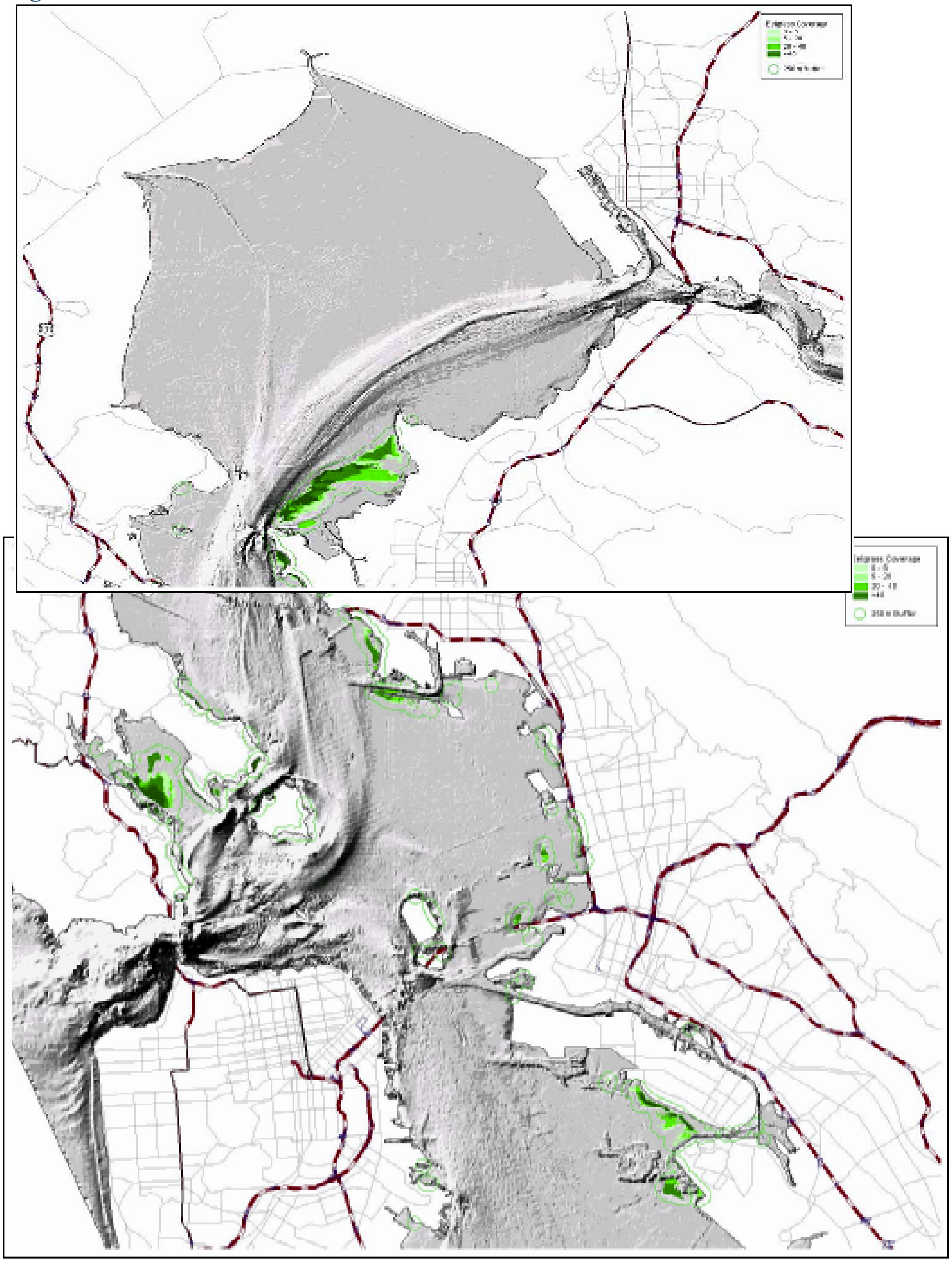

Figure 2-8. Eelgrass beds in San Francisco Bay (Merkel & Associates 2004)

Depth is thought to be a major factor in determining suitable herring spawning habitat. Herring spawn both in intertidal and subtidal areas of the Bay. Subtidal spawns are monitored during DFG spawn surveys to a depth of approximately < 4.5 meters, a level thought appropriate in the relatively turbid waters of San Francisco Bay (Watters *et al.* 2004, Spratt 1981). In the clearer waters of British Columbia, evidence suggests that most spawning occurs at depths less than 10 meters (Doug Hay, personal communication).)

Rooper *et al.* (1999) found that depth of spawn (or time of air exposure) was the most important variable in determining egg survival in Prince William Sound, presumably because predation by gulls during exposure could decimate the population. (Wave exposure, substrate type, and kelp type were insignificant.) McGurk *et al.* (1993) found that larvae with low condition in Auke Bay, Alaska came primarily from cohorts with eggs laid high in the intertidal zone. They suggested that desiccation and temperature extremes could disrupt development and produce larvae that are not able to take advantage of the abundant available food.

Nursery grounds. The success of Atlantic and Pacific herring larvae and juveniles in reaching appropriate nursery habitat has also been discussed in the literature (*e.g.*, Hay and McCarter 1997). In British Columbia, the North Sea, and the Baltic Sea, older larvae move from more pelagic to nearshore waters. In British Columbia, larger juveniles tend to be in deeper waters while smaller juveniles stay closer to shore (Doug Hay, personal communication). However, there have been no studies of larval retention in San Francisco Bay and relatively little work on the ecology of juveniles. Juvenile herring are taken in USFWS beach seines (Figure 2-9), but the data are limited, do not include open water areas, and are not meant to quantify herring juvenile abundance or nursery grounds.

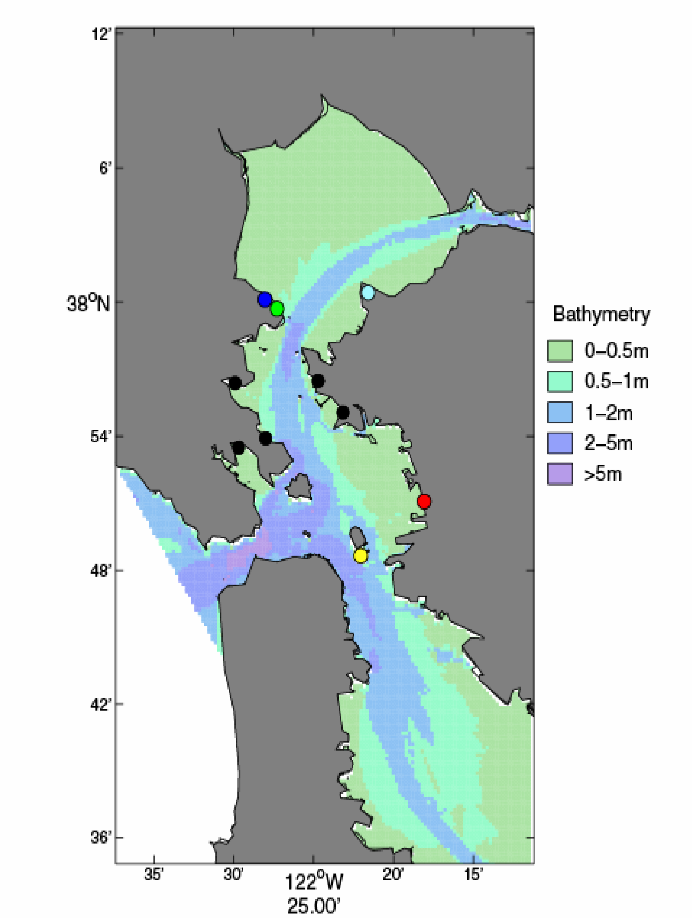

Figure 2-9. Sites with juvenile herring in 1976, 1980, and 1997-2004 beach-seine surveys (from USFWS). Colored dots denote sites with relatively frequent catches and correspond to colors in Figure 2-10. Black dots indicate sites of infrequent herring catch.

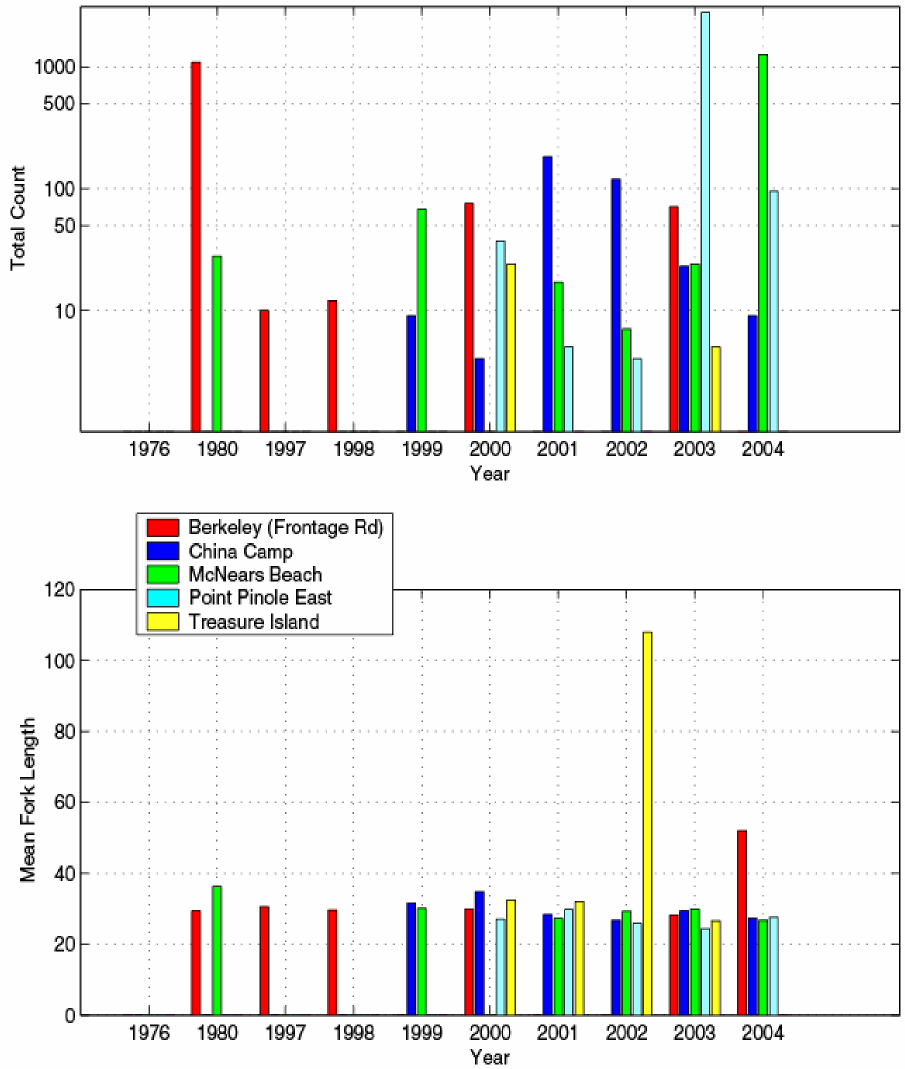

Figure 2-10. Abundance and length of Pacific herring juveniles in San Francisco Bay 1976, 1980, and 1997-2004 (from USFWS)

2.6 Effects of Suspended Solids and Sedimentation

Effects of suspended solids and sedimentation on the egg, developing embryo, and larval life stages of Pacific herring were the focus of DFG's rationale for restricting dredging in San Francisco Bay; potential effects have been reviewed by Ogle (2004) (Table 2-1).

Table 2-1. Environmental responses of Pacific and Atlantic herring to suspended sediments (from Ogle 2004)

Response	Suspended sediment concentration	Comments	Reference
Migration to spawning sites			
Avoidance	9-12 mg/L	Juvenile Atlantic herring were observed to exhibit avoidance response.	Johnson and Wildish 1981
Exhibition of appropriate spawning behavior			
Tactile acceptance of spawning substrate	unknown	Hypothesized that presence of sediment on substrate could inhibit spawning.	Stacey and Hourston 1982
Fertilization of eggs			
Sperm activation	unknown	Particulate matter may adhere to sperm surface and prevent activation.	Vines *et al.* 1966a
Development, survival and hatching of embryos			
No effect	~7300 mg/L	No effect on hatch success, slight reduction in time to hatch at highest concentration tested.	Messieh *et al.* 1981
No effect	300 mg/L continuous; 500 mg/L pulses	No effects on embryo survival, successful hatch, of size of hatched larvae.	Kiorboe *et al.* 1981
No effect	500 mg/L static; 8000 mg/L continuous	No significant effect of embryo mortality, hatch rate, of embryonic deformities.	Boehlert *et al. 1983*
No effect	4000 mg/L	No significant effect on mortality or hatch rate. Sediments used in study were acknowledged to be contaminated.	Morgan and Levings 1989
No effect	2000 mg/L	No effects on survival or hatch. Test medium was sewage sludge.	Costello and Gamble 1992
Survival of larval fish			
Reduced survival	6000 mg/L	No effect at 700 mg/L.	Messieh *et al.* 1981
Epidermal damage	4000 mg/L	No effect on survival at 8000 mg/L.	Boehlert 1984
Reduced survival	500 mg/L	Sediment was acknowledged to be contaminated.	Morgan and Levings 1989
No effect	2000 mg/L	Test medium was sewage sludge.	Costello and Gamble 1992
Larval feeding			
Increase	500 and 1000 mg/L	Increase in percentage fish that fed; increase in number of prey items consumed at 500 mg/L.	Boehlert and Morgan 1985
Reduced feeding	20 mg/L	Authors cautioned that their results were inconclusive.	Johnston and Wildish 1982

Potentially, high levels of suspended solids or sedimentation could affect gonad maturation, spawning behavior, adhesion of eggs to appropriate substrates, egg viability, or larval feeding. Ogle (2004) found no information about gonad maturation or egg adhesion. Most of the studies he reviewed found no adverse effects of suspended sediments. Effects were noted by Johnson and Wildish (1981) who reported avoidance responses in juveniles and reduced feeding in larval Atlantic herring exposed to low levels of suspended solids. Messieh *et al.* (1981) reported apparent reduced survival of Atlantic herring larvae exposed to 6,000-19,000 mg/L suspended solids, and Morgan and Levings (1989) found reduced survival in Pacific herring larvae exposed to 500 mg/L "contaminated" sediment.

Spawning behavior. Stacey and Hourston (1982) observed that Pacific herring assess the spawning surface and that sediment on the substrate may inhibit the early stages of a spawning episode. Conceivably, intense sediment confined to a small area would be less likely to affect spawning behavior than the same amount of sediment distributed over a larger area (Doug Hay, personal communication), and once spawning has commenced, effects of suspended solids or sedimentation are unlikely.

Egg viability. Theoretically, suspended solids could affect egg adhesion, fertilization, development, or hatching. Auld and Schubel (1978) exposed eggs and larvae of six species of East coast anadromous and estuarine fishes to concentrations of suspended sediments ranging from a few mg to 1000 mg/L. Concentrations of up to 1000 mg/L did not affect hatching success of yellow perch, blueback herring, alewife, or American shad eggs. Concentrations of 1000 mg/L did affect hatching rates of white perch and striped bass. Kiørboe *et al.* (1981) exposed Atlantic herring eggs to silt in constant concentrations of 5-300 mg/L or short pulses of 500 mg/L and found that the embryos were unaffected. In another laboratory study, Messieh *et al*. (1981) found that survival of Atlantic herring eggs was limited to the surface layers when the eggs were laid in multiple layers and that a thin film of fine sediments could also affect hatching success. No sediments were attached to the surviving eggs. In a field study, Morrison *et al.* (1991) found 98% mortality of Atlantic herring eggs following a diatom bloom. The eggs were covered with approximately 1 mm of organic matter, which was composed of decaying diatoms and other unidentified cellular fragments. The authors suspected that anoxia was the cause of the mortality and further, that low oxygen levels resulted in delayed egg development.

Similar to the effects of sedimentation, smothering by other eggs can also result in egg mortality. In a review paper, Alderdice and Hourston (1985) found that increased thickness of spawn led to lower survival of occluded eggs. Reduced oxygen levels in the egg mass may lead to slower development of occluded eggs (Doug Hay, personal communication, reviewed by Alderice and Hourston 1985). Hourston *et al.* (1984) found that egg survival decreased at increased egg densities and that this decline varied with the type of spawning substrate. Egg densities of between 20 and 30 layers have been associated with almost complete mortality of both Atlantic and Pacific herring eggs (Messieh and Rosenthal 1989, Galkina 1971). Herring egg deposition in San Francisco Bay does not reach densities of 20 to 30 layers (DFG, personal communication).

Larval feeding. Boehlert and Morgan (1985) exposed Pacific herring larvae to suspensions of estuarine sediments and Mount Saint Helens ash at concentrations ranging from 0 to 8000 mg/L. In all their experiments, maximum feeding incidence and activity occurred at 500 or 1000 mg/L. Feeding decreased at concentrations higher than 1000 mg/L. They postulated that herring larvae were adapted for feeding in turbid estuarine environments. Conversely, Johnson and Wildish (1982) found reduced feeding in Atlantic herring larvae exposed to 20 mg/L suspended solids (though the authors cautioned that their results were inconclusive).

Ambient conditions in San Francisco Bay. San Francisco Bay has naturally high levels of suspended sediments (Figure 2-11). No specific information on suspended solids in herring spawning areas at the time of spawning or larval development is available.

Figure 2-11. Aerial view of the San Francisco Bay estuary (USGS Toxic Substances Program)

In shallow embayments, such as San Pablo and Suisun bays (north of the areas in which herring spawn), wind-waves, freshwater Delta outflow, and tidal flows are the main natural sources of sediment resuspension (O'Connor 1991). The Central Bay is deeper and not as dominated by wind-driven resuspension, and suspended sediment concentrations are lower (Schoellhamer 2002, O'Connor 1991).

Half the variability in suspended solids concentrations in San Francisco Bay results from the spring-neap tidal cycle; in San Pablo Bay, solids resuspension from the spring-neap tidal cycle can affect suspended solids concentrations for up to a few days (Schoellhamer 1995, 2002). Delta outflow also affects suspended sediments loads. Delta outflow is relatively fast in the more constricted areas of the Bay, such as Carquinez Strait, and diminishes when entering the broader expanses of San Pablo Bay and the Central Bay (Sustar 1982).

USGS data show that the daily average suspended sediment concentrations at Point San Pablo and at Pier 24 on the San Francisco waterfront vary within and between years (Table 2-2, Figure 2-12; Buchanan and Schoellhamer 1996, Buchanan and Schoellhamer 1999, Buchanan and Ganju 2002). During water year 1997, which had greater than average Delta outflow, maximum concentrations of suspended solids were 1600-1700 mg/L at Point San Pablo and 200-650 mg/L at Pier 24, occurring during strong winter storms. In 2000, maximum concentrations of suspended solids were lower at both locations. The durations of the maximum in situ suspended sediment concentrations were short and probably associated with strong winter storms. Suspended solids concentrations in a range 50-200 mg/L were sustained for longer periods of time.

Table 2-2. Estimated maximum suspended solid concentrations (1997 & 2000) at mid depth and near bottom depth for Point San Pablo (13 feet from bottom and 3 feet from bottom) and Pier 24 (23 feet from bottom and 3 feet from bottom) (courtesy of USGS)

Sample Location	Water Year	Sample Depth	Estimated Maximum Concentration in mg/L	Mean concentration in mg/L	Median concentration in mg/L
Point San Pablo	1997	mid-depth	1600	112	77
Point San Pablo	1997	near-bottom	1700	144	105
Pier 24	1997	mid-depth	200	28	27
Pier 24	1997	near-bottom	650	47	36
Point San Pablo	2000	mid-depth	400	43	40
Point San Pablo	2000	near-bottom	480	59	47
Pier 24	2000	mid-depth	130	23	21
Pier 24	2000	near-bottom	230	32	28

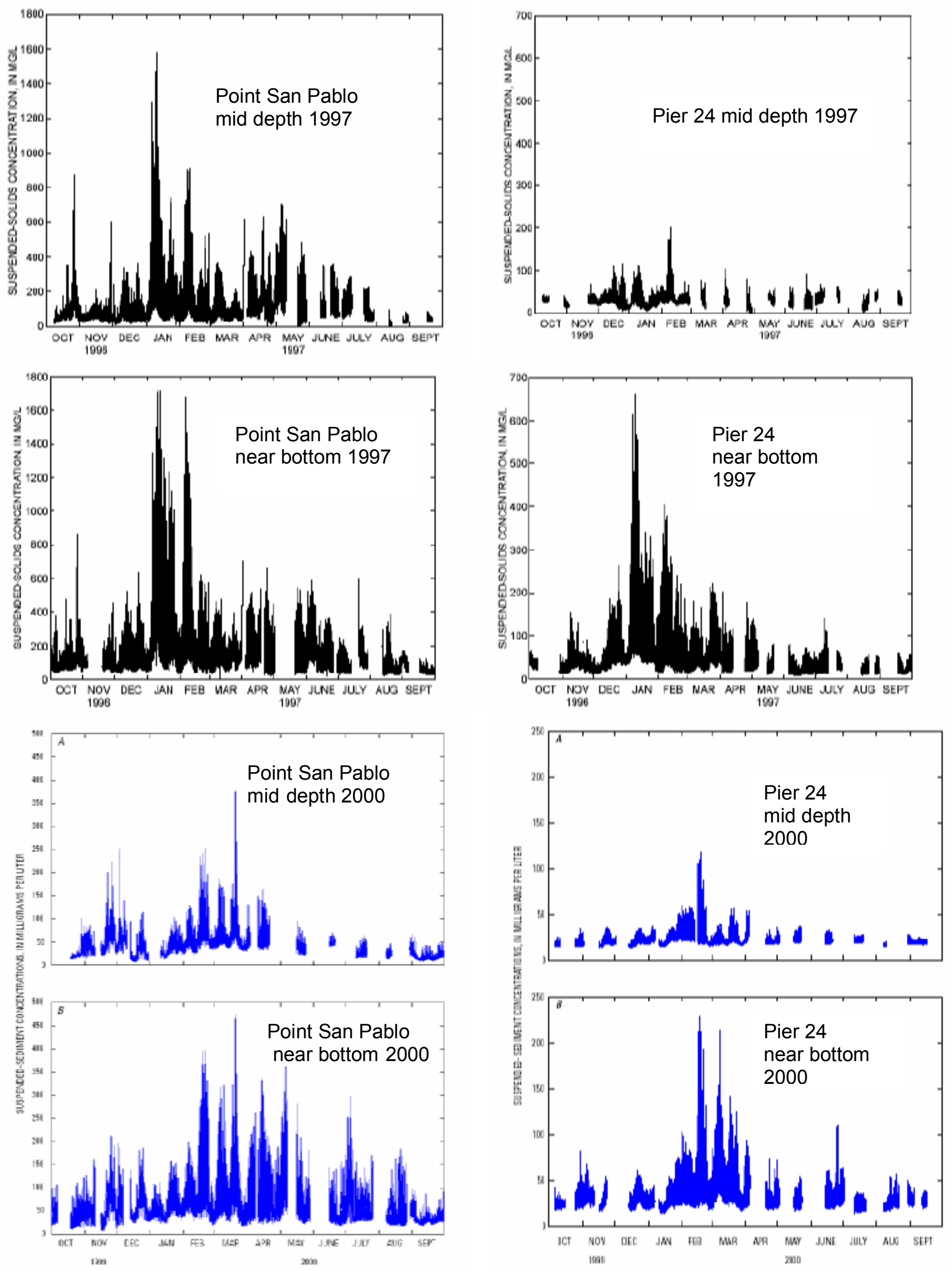

Figure 2-12. Suspended sediment concentrations at Point San Pablo and Pier 24 in 1997 and 2000. Note differences in scales. (Buchanan and Schoellhamer 1999, Buchanan and Ganju 2002)

Whether these naturally occurring maximum levels of suspended solids affect Pacific herring in the Bay is not known. The highest measured values are below the levels found to affect survival by Messiah *et al.* (1981) but in the range found to have an effect by Morgan and Levings (1989, for contaminated sediments). Some of the measurements are within the range found by Boehlert and Morgan (1985) to stimulate feeding.

Suspended sediments are discussed further in Section 3.1, Suspended Solids and Sedimentation from Dredging. The section includes a discussion of the relative effects of dredging and natural events on resuspension and revisits the question of whether suspended solids may affect Pacific herring in the Bay.

2.7 Effects of Contaminants

Because San Francisco Bay is an urban estuary, Pacific herring can be expected to be exposed to chemical contaminants from a variety of sources; Central San Francisco Bay is listed by USEPA and SWRCB as impaired by legacy pesticides (DDTs, chlordanes, and dieldrin), diazinon, mercury, selenium, dioxins, and PCBs. Kocan and Landolt (1988) have suggested that Pacific herring embryos may be sensitive indicators of presence of toxic contaminants in the environment.

Because of their importance in the Puget Sound food web, the State of Washington Puget Sound Ambient Monitoring Program monitors PCBs and pesticides in adult Pacific herring (O'Neill and West 2001). Maximum whole body PCB concentrations have been as high as 200.2 µg/kg wet weight, higher in fish from areas with more contaminated sediments, but below an adverse effects threshold developed by NMFS. Like Puget Sound, San Francisco Bay has elevated levels of several contaminants. Adult herring are in the Bay for a short period of time and therefore exposure time to potential contaminants is short. However, juveniles are potentially exposed to contaminants for longer periods of time. In a recent screening survey of Pacific herring caught from San Francisco Bay, contaminants were identified in 1 whole-body composite (caught as bycatch). Total DDTs, total PCBs, total aroclors (commercial PCB mixtures), and PBDEs were identified in this composite (RMP, unpublished data). The data are limited and no extrapolation to effects, at the individual or the population level, can be made.

Creosoted pilings. Pacific herring in San Francisco Bay, particularly along the San Francisco waterfront, spawn on pilings, so effects of exposure to compounds in creosote is of special concern. Vines *et al.* (2000) examined the effect of diffusible creosote-derived compounds on herring embryonic development and found reduced hatch success of embryos exposed to creosote-treated wood in the laboratory. Larvae that hatched exhibited morphological abnormalities; effects were dependent on whether the embryos were in contact with the creosote-treated wood. Under field conditions in San Francisco Bay, Vines *et al.* (2000) found greater hatching success in the field compared to laboratory experiments, presumably because water flow lessened exposure to toxic compounds. Further studies of eggs deposited onto pilings and larval success are warranted; conceivably, hatching success on these pilings is lower than on natural substrates.

Oil spills. Most of the work on the effects of contaminants on Pacific herring was conducted in the aftermath of the *Exxon Valdez* oil spill in Prince William Sound, Alaska (Tables 2-3, 2-4).

Understanding the results of these hydrocarbon toxicity studies requires an understanding of the toxicant composition and exposure methodology. Aromatic hydrocarbons (benzene, ethyl-benzene, toluene, and xylene, often referred to as BTEX, and polynuclear aromatic hydrocarbons or PAH) are recognized as primary toxins in crude oil. A long and growing line of evidence demonstrates that aromatic hydrocarbon toxicity increases with molecular size and alkyl-substitution (*e.g*., Anderson *et al.* 1974, Moore and Dwyer 1974, Rice *et al*. 1977, Black *et al.* 1983). BTEX are more water soluble, enter the water column easily, and are usually thought to be more acutely toxic. In contrast, the multi-ringed compounds are probably more responsible for chronic damage, making animals less fit for survival.

Interaction of oil and water controls entry of constituents into water. Various established methods yield very different suites of hydrocarbons in water. How well different approaches emulate environmental conditions is of great interest. An aqueous PAH composition caused by passage of water through oiled rock was consistent with the composition found intertidally after the *Exxon Valdez* oil spill and with the enrichment of lower molecular weight PAHs in the water column. A low-energy mixing technique emulated conditions found after a spill with mild mixing conditions and little physical dispersion (Neff *et al.* 2000), a situation that lasted only days before a major storm dispersed the oil into the water column and over such a broad area that containment was not feasible (Spies *et al.* 1996). The complexities of oil-water interactions must be addressed in any numerical summaries of toxicity.

Table 2-3. Toxicity tests conducted on Pacific herring

Life Stage	Contaminant Concentration in ppm	Type of Oil	Effect	Exposure Duration	Reference
Eggs	0.0173	Alaska North Slope crude oil; weathered WAF	edema	4 days	Barron et al., 2003
Eggs	0.038	Alaska North Slope crude oil; weathered WAF	LC_{50}	8 days	Barron et al., 2003
Eggs	0.0007[b]	Alaska North Slope crude oil; weathered WSF; water through oiled gravel	malformations, genetic damage, mortality, decreased size, inhibited swimming	16 days	Carls et al., 1999
Eggs	≥0.0004	Alaska North Slope crude oil; weathered WSF; water through oiled gravel	yolk-sac edema, immaturity	16 days	Carls et al., 1999
Eggs	9.1	Alaska North Slope crude oil; weathered WSF; water through oiled gravel	abnormalities, growth, mortality	16 days	Carls et al., 1999
Eggs	0.058	Alaska North Slope crude oil; weathered WSF; water through oiled rock	no effect	16 days	Carls et al., 2000
Eggs	>0.24	Prudhoe Bay crude oil; OWD	premature hatching (4-5 days early)	15 days (mean value)	Kocan et al., 1996
Eggs	0.24-0.97	Prudhoe Bay crude oil; OWD	sig increase in proportion of physically deformed larvae	13-22 days	Kocan et al., 1996
Eggs	0.1-9.67	Prudhoe Bay crude oil; OWD	no sig. effect on hatching success	13-22 days	Kocan et al., 1996
Eggs	0.43	Prudhoe Bay crude oil; OWD	EC_{50}	13-22 days	Kocan et al., 1996
Eggs	In situ	Oiled and non-oiled sites in PWS (1991 sampling)	lower hatch success in-situ compared to lab controls and lab exposre to oil treatments	8-12 days	Kocan et al., 1996
Eggs	In situ	Oiled and non-oiled sites in PWS (1991 sampling)	lower percent normal development of larvae at oiled vs non-oiled sites. Oil % normal development in the range of lab controls and 0.10-1.0 mg/L oil exposure.	8-12 days	Kocan et al., 1996
Eggs	In situ	Oiled and non-oiled sites in PWS (1991 sampling)	no sig. difference between oiled and non-oiled sites.	8-12 days	Kocan et al., 1996
Eggs	In situ	Oiled and non-oiled sites in PWS (1991 sampling)	Sig. lower mean dry weights of larvae for oiled sites vs. non-oiled sites.	8-12 days	Kocan et al., 1996
Eggs	0.004	Whole oil; WSF	abnormalities	~13 days	Pearson et. al., 1985
Adult-prespawn	2.3	Cook Inlet crude oil; WSF	LC_{50}	2 and 12 days	Rice et al., 1987
Adult	1.6	Cook Inlet crude oil; WSF	no effect	12 days	Rice et al., 1987
Egg hatching	5.3	Cook Inlet crude oil; WSF	no effect	2 days	Rice et al., 1987
Egg hatching	1.5	Cook Inlet crude oil; WSF	LC_{50}	12 days	Rice et al., 1987
Yolk-sac larvae	6.1	Cook Inlet crude oil; WSF	no effect	<=6 hours	Rice et al., 1987
Yolk-sac larvae	2.8	Cook Inlet crude oil; WSF	LC_{50}	16 hours	Rice et al., 1987
Yolk-sac larvae	2.3	Cook Inlet crude oil; WSF	LC_{50}	6 days	Rice et al., 1987
Feeding larvae	1.8	Cook Inlet crude oil; WSF	LC_{50}	7 days	Rice et al., 1987
Feeding larvae	0.36	Cook Inlet crude oil; WSF	LC_{50}	21 days	Rice et al., 1987
Larvae	0.3	Cook Inlet crude oil; WSF	reduced growth	7 days	Rice et al., 1987
Larvae	il-contminated pre	Cook Inlet crude oil; WSF	no reduced growth		Rice et al., 1987
WSF-water soluble fraction					
WAF-water-accomadated fraction					
OWD=oil-water dispersions					
b=initial aqueous concentrations					

Table 2-4. Toxicity tests conducted on other species (provided by J. Rice)

Species	Biological Measurement	Conc µg/L	Chemical Measurement and Method	Reference and Type of Oil
Atlantic cod (*Gadus morhua*)	Growth	50	primarily mono-aromatics, embryo-larval exposure (14 d), WSF	Tilseth *et al.* 1984 Ekofisk oil
Pink salmon (*Oncorhynchus gorbuscha*)	ascites, premature emergence, gonadal cell apoptosis, induction of CYP1A	4.4	TPAH, weathered oil, embryo-larval exposure (177 d), ORC	Marty *et al.* 1997 Alaska North Slope crude
	Mortality	52	TPAH, embryo-larval exposure (177 d), ORC	Marty *et al.* 1997 Alaska North Slope crude
	Mortality	1.0	TPAH, very weathered oil, embryo-larval exposure (~ 8 mo), ORC	Heintz *et al.* 1999 Alaska North Slope crude
	Mortality	18.0	TPAH, weathered oil, embryo-larval exposure (~ 8 mo), ORC	Heintz *et al.* 1999 Alaska North Slope crude
	marine survival	5.4	TPAH, weathered oil, embryo-larval exposure (~ 8 mo), ORC	Heintz *et al.* 2000 Alaska North Slope crude
	post-emergent growth	18	TPAH, weathered oil, embryo-larval exposure (~ 8 mo), ORC	Heintz *et al.* 2000 Alaska North Slope crude
Fathead minnow (*Pimephales promelas*)	decreased survival in F2 generation	1.0	benzo(a)pyrene, larval exposure of parent fish (4 mo)	White *et al.* 1999
Japanese medaka (*Oryzias latipes*)	Neoplasms	30-50	benzo(a)pyrene, larval exposure (6 h weekly for 2-4 weeks)	Hawkins *et al.* 1990
Copepod *Eurytemora affinis*	survival, egg production, nauplii production	10	naphthalenes, (~ 1 mo)	Ott *et al.* 1978
nauplii, primarily *Acartia* sp. and *Pseudocalanus* sp.	Mortality	75	naphthalenes (~40 d)	Lee *et al.* 1978
Copepod *Centropages hamatus*	decreased ingestion rates and decreased egg viability	10 to 80	crude oil/seawater dispersions	Cowles & Remillard 1983
Copepod *Centropages hamatus*	altered swimming activity	80	crude oil/seawater dispersions	Cowles 1983
Diatom (*Ceratualina* sp.)	Mortality	40	WSF, No. 2 Fuel oil (~2 weeks)	Lee *et al.* 1977

WSF is water-soluble fraction. ORC is oiled-rock column assay. WAF is water-accommodated fraction. "Weathered oil" is indicated in studies where the BTEX fraction was removed by heating prior to experimentation. Further pretreatment weathering occurred in flowing water several days before assays began. "More weathered" oil was further weathered by flowing water (17 d). "Very weathered" oil was weathered 1 year by water passage through oiled rock.

Weathering of oil spilled into the environment also influences the composition of oil (model by Short and Heintz 1997, and laboratory studies by NMFS). The conclusion reached by these studies is that PAHs transferred from oiled sediment into water are bioaccumulated and highly toxic to embryonic fish, including Pacific herring (lowest observed effective concentration ranged from 0.4 to 18 µg/L; Marty *et al.* 1997, Carls *et al.* 1999, Heintz *et al.* 1999, Heintz *et al.* 2000). Carls *et al.* (2002) demonstrated that oil-contaminated water in Prince William Sound contained the same toxic PAH constituents and adversely affected the herring spawn in oiled areas. The most persistent PAHs were also the most toxic.

Hydrocarbon composition controls toxicity. Highly volatile BTEX are rapidly toxic and typically narcotize animals. In contrast, the PAHs can not only contribute to narcosis effects, they can cause cancer, oxidative stress through photo-enhanced toxicity, and a wide spectrum of developmental disorders to exposed embryos of aquatic animals including fish. That PAHs were the critical long-term toxicants, not BTEX or other oil constituents, was a consistent finding from the *Exxon Valdez* experience.

How an assay is conducted strongly affects the outcome. Commonly used acute assays to determine median lethal concentrations (LC50s) were adopted for convenience and ignored delayed and sublethal responses (Zhao and Newman 2004). Failure to observe delayed responses limits the usefulness of short-term assays. Failure to observe sublethal effects also overlooks the true implications of exposure; detrimental sublethal effects typically occur at concentrations well below lethal levels. Heintz *et al.* (2000) demonstrated the combined result of both these concepts; the number of adults that returned to spawn was significantly reduced by embryonic exposure to oil, yet all tagged fry were apparently healthy at the time of release. Long-term observations should be given more weight when determining safe concentration levels.

Estimates of species sensitivity are influenced by the life stage assayed. Embryos and larvae are often more sensitive to pollutants than later life stages (*e.g.*, Moore and Dwyer 1974, Weis and Weis 1989). Substances that cause developmental defects are particularly damaging to developing embryos, and the ability of petroleum hydrocarbons to cause such abnormalities has long been known (*e.g.,* Kuehnhold 1972). Early life stage should be emphasized when formulating safe limits.

Other toxicity studies. Exposure to chronic, low levels of other contaminants can lead to bioaccumulation of some compounds, such as PCBs, organochlorine pesticides, and methyl mercury. Pacific herring eggs have been successfully used for in situ and in vitro toxicity tests in the Pacific Northwest. Herring eggs showed acute responses to contaminated water and sediments (Kocan and Landolt 1988, Kocan *et al*. 1996). In situ exposed eggs (96 hours) had a significant increase in mortality at three contaminated sites in Puget Sound compared with controls. Larval abnormalities were significantly higher and hatching success significantly lower in herring embryos exposed for 72 hours to contaminated sites in the field and then hatched in the laboratory. In vitro tests for contaminated water and sediment elutriate exposed eggs had significantly higher incidence of larval abnormalities at two of the three sites. The source of toxicity was not identified but the sites chosen were known for past herring egg mortality. The authors concluded that herring mortality and teratogenic effects were probably due to a water soluble toxic substance.

No studies of toxic effects on Pacific herring in San Francisco Bay are available. In the Sacramento splittail (*Pogonichthys macrolepidotus*, a fish endemic to the San Francisco Estuary), abnormalities such as skeletal deformities, abnormal feeding and swimming, and pericardial edema have been associated with long-term contaminant exposure tests (5 to 9 months) and longer-term evaluations beyond normal acute toxicity testing (evaluation up to 3 months after end of toxicity tests) of selenium, diazinon, and esfenvalerate and could have potential effects at the population level (Teh *et al.* 2002, 2004a, 2004b, in press).

Resuspension of contaminated sediment: ambient conditions in San Francisco Bay. One issue of concern for San Francisco Bay is the effects of resuspension of contaminated particulate material on various life stages of Pacific herring. Bay sediments are contaminated with PAHs, PCBs, mercury, and pesticides.

Toxicity tests using whole sediments conducted by the Regional Monitoring Program for Trace Substances (RMP), which monitors contaminant concentrations in the water, sediments, fish, and shellfish of the Bay, has found that the most toxic sediments are in the Carquinez Strait, Suisun Bay and the Delta, all of which are north and upstream of the herring spawning areas (Figure 2-13). Due to contamination, fishing is prohibited along the shoreline of Hunter's Point Naval shipyard, which is south of the San Francisco waterfront and a site of herring spawning (DFG, personal communication).

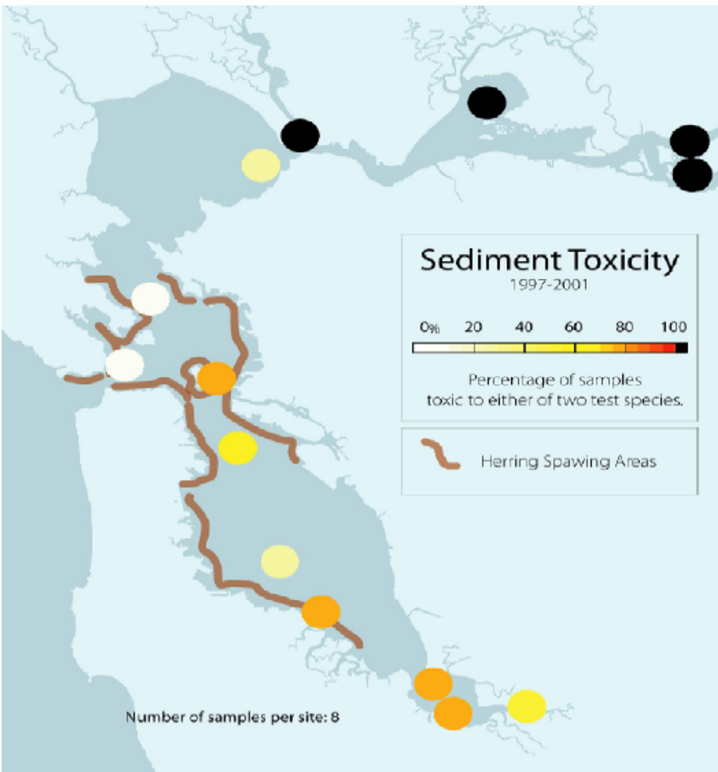

Figure 2-13. Percentage of samples at RMP sediment sampling sites toxic to test species

Concentrations of total PAHs are patchy throughout the Bay and have remained relatively constant over the time period of the RMP, 1991-2003 (Oros and Ross 2004). Mean concentrations in the Central Bay sediments have been as high 230 mg/kg total organic carbon.

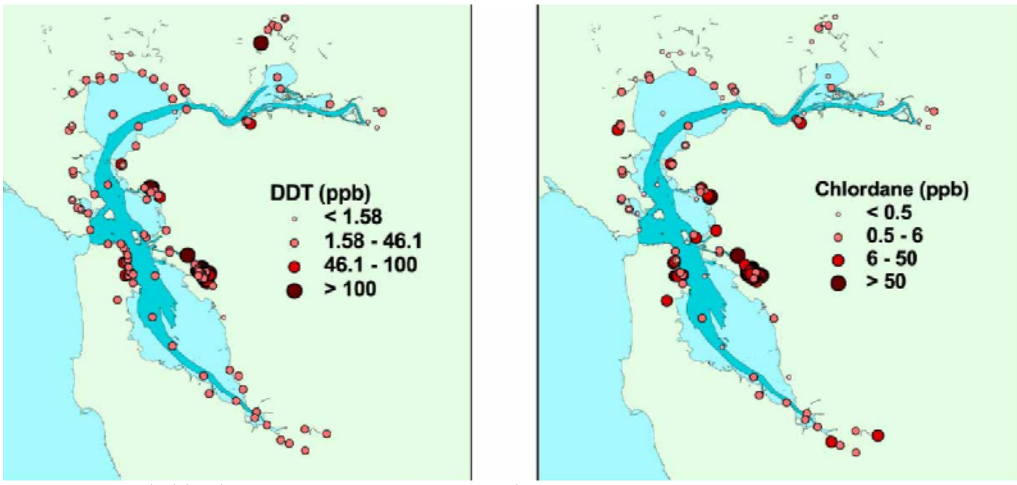

Figure 2-14. DDT and chlordane concentrations in Bay sediment, 1991-1999

Concentrations of many contaminants, such as PCBs (Figure 2-15) and pesticides (Figure 2-14) tend to be higher in the shallow areas at the urbanized edges of the Bay, which are also targets for dredging and herring spawning locations. The potential for resuspension of contaminants through dredging is discussed further in Section 3.3.

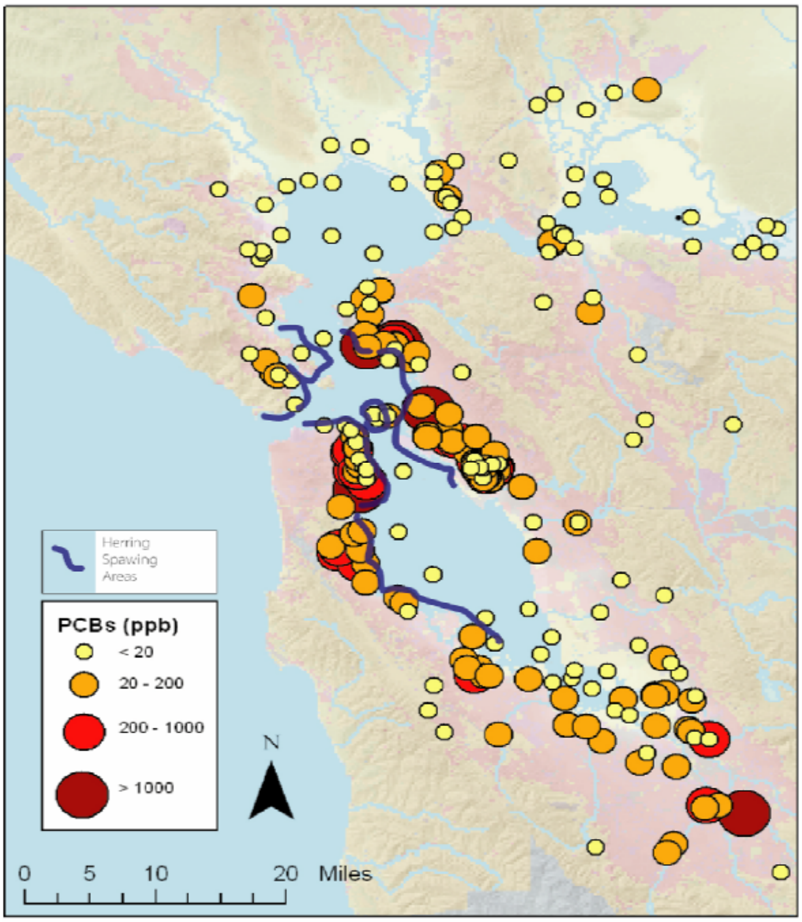

Figure 2-15. Sediment and soil PCB concentrations (RMP data)

2.8 Effects of Noise

There are no documented cases of Pacific herring populations being affected by noise. Sound detection in fish is usually limited to frequencies less than 400 Hz. However, Blaxter and Hunter (1982) found that sound reception in Pacific herring is well developed. Pacific and Atlantic herring have been demonstrated to respond to sound from boats, fishing tackle, sonar equipment, and acoustic deterrent devices. Short duration, low frequency sounds tend to produce startle responses, while longer duration, high frequency sounds produce avoidance responses, such as compacting of the school, sinking in the water, or leaving the area (information summarized by Wilson and Dill 2002). Recent studies have suggested that herring may use sound to communicate within a school (Wilson *et al.* 2003).

Noise in busy coastal harbors generally reaches loudness of about 100 dB, peaking at 150 dB in major ports; marine engine noise is in a frequency band of 10-2000 Hz (Michael Stocker Associates, www.msa-desgn.com). Pacific herring in pens have been observed to avoid sounds ranging from 1600-3000 Hz, corresponding to the presence of large vessels (Schwarz and Greer 1984). Avoidance of large vessel sounds ended within 10 seconds after the vessel began to depart and noise intensity decreased. Disturbed herring did not approach the surface for 1-3 minutes after departure. Fewer herring responded to transmittal of sounds from smaller vessels.

During the Pile Installation Demonstration Project conducted for a 2001 Fisheries Impact Assessment to determine potential effects of pile driving for the San Francisco-Oakland Bay Bridge construction project, young-of-the-year or yearling herring were found moribund or dead following an experiment with a small hammer and experiments with a small hammer plus a bubble curtain (Caltrans 2001). The pile-driving sound fell in a frequency range of 80-1250 Hz. The maximum instantaneous sound pressure during the experiment, resulting in dead or moribund herring, was 199-201 dB re 1 uPa-m at a distance of 206 meters. The root mean square impulse for the same experiment ranged from 187-190 dB re 1 uPa-m.

The Pile Installation Demonstration Project also experimented with caged shiner surfperch at distances closer to the source. In experiments under similar conditions, fish injury (light hemorrhaging, principally in tissue covering the kidneys) ranged from 0% (at 150 m for 34 minutes) to 80% (at 30 and 50 meters for 57 minutes).

The potential effects of sound produced during dredging is discussed in Section 3.3.

3. Possible Effects of Dredging

Dredging may increase suspended sediment concentrations, release sediment-bound contaminants to the water column, depress dissolved oxygen levels, and increase noise in localized areas. Theoretically, these factors could affect fish at any life stage occurring in the Bay (Figure 3-1). The environmental work window presumes that spawning adults and eggs are the most vulnerable life stages. Larvae, which lack the mobility to avoid dredge plumes, and juveniles may also be vulnerable. Since embryonic, larval, and juvenile stages occur in nearshore areas, effects of dredging in marinas may be more significant than large volume dredging in shipping channels (Jeep Rice, personal communication).

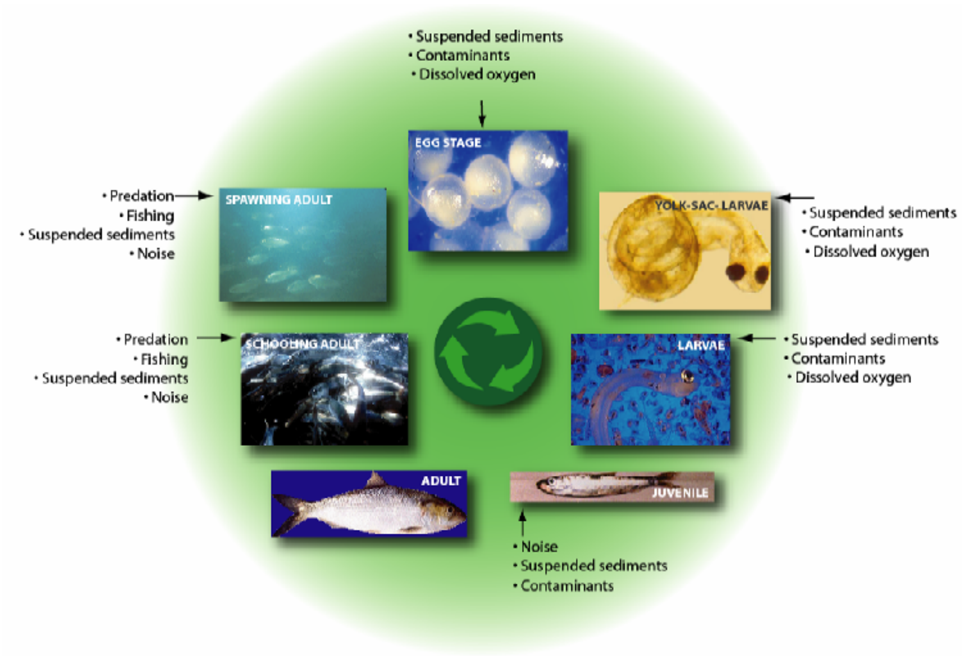

Figure 3-1. Potential dredging-induced factors affecting Pacific herring

This section focuses specifically on the possible effects of dredging on Pacific herring. It repeats some of the topics of Section 2, Factors that Affect Herring Populations, including suspended solids and sedimentation, contaminants, and noise, and adds a section on dissolved oxygen concentrations, which DFG has identified as an additional factor that may be affected by dredging.

3.1 Suspended Solids and Sedimentation from Dredging

Potential effects of suspended solids and sedimentation on spawning behavior, egg viability and feeding was the major concern that led to the development of the environmental window, and possible effects have been reviewed by Ogle (2004; Figure 3-2).

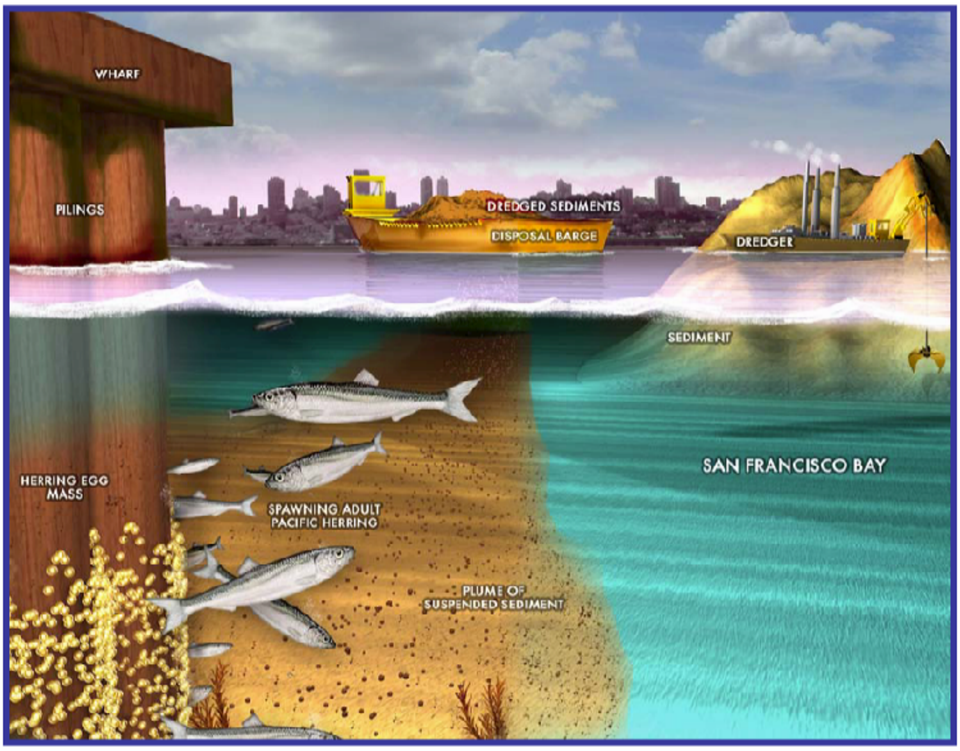

Figure 3-2. Potential effects of suspended solids from dredging operations (Ogle 2004)

Several studies of sediment resuspension during dredging have been conducted by USACE and other researchers (*e.g.*, McLellan *et al.* 1989, Table-3-1). Van Oostrum and Vroege (1994) estimated that 0-5% of dredged material is resuspended during the dredging process.

Table 3-1. Suspended sediments released during dredging operations (from McLellan et al. 1989)

Dredge Equipment	Dredge Type	Study Location	Suspended Sediment Concentration (mg/L)	Ratio of Max Concentration to Background Concentration	Location
Cutterhead, 12 inch	Hydraulic	Calumet Harbor	5		Surface
Matchbox	Hydraulic	Calumet Harbor	2.5		Surface
Cutterhead, 18 inch	Hydraulic	Savannah River	20		Surface
Cutterhead, 18 inch	Hydraulic	James River	40		Surface
Dustpan	Hydraulic	James River	60		Surface
Cutterhead, 12 inch	Hydraulic	Calumet Harbor	10	2	Bottom
Matchbox	Hydraulic	Calumet Harbor	15.5	2.9	Bottom
Cutterhead, 18 inch	Hydraulic	Savannah River	120	1.8	Bottom
Cutterhead, 18 inch	Hydraulic	James River	200	2.5	Bottom
Dustpan	Hydraulic	James River	340	3.8	Bottom
Open Bucket	Mechanical	Calumet River	20		Minimum Contour
Open Bucket	Mechanical	Black Rock	80		Minimum Contour
Open Bucket	Mechanical	Duwamish Waterway	20		Minimum Contour
Open Bucket	Mechanical	St John's River	70		Minimum Contour
Enclosed Bucket	Mechanical	St John's River	50		Minimum Contour
Open Bucket	Mechanical	Calumet River	140	11.7	Maximum Contour
Open Bucket	Mechanical	Black Rock	1100	15.9	Maximum Contour
Open Bucket	Mechanical	Duwamish Waterway	160	6.1	Maximum Contour
Open Bucket	Mechanical	St John's River	480	6.7	Maximum Contour
Enclosed Bucket	Mechanical	St John's River	380	5	Maximum Contour

Local studies. A recent study in Oakland Harbor monitored levels of total suspended solids during dredging by a mechanical dredge during ebb and flood tides (MEC-USACE Research and Development Center 2004). Current velocities were relatively weak (less than 25 cm/sec) during the study and conditions were conducive to keeping suspended material close to the dredge. Concentrations of total suspended solids exceeding background levels (> 50 mg/L) were detected up to 400 meters from the dredge during both ebb and flood tides. Levels greater than 100 mg/L were distributed in small pockets, mostly near the bottom, and levels above 275 mg/L were found only in the immediate vicinity of the dredge. Duration of the plumes, which is typically dependent on the production rate of the dredge and the volume of the sediment dredged, was not measured.

In his review of the potential effects of suspended solids from dredging on Pacific herring, Ogle (2004) compared results from the Oakland Harbor study (MEC-ERDC 2003) to field and laboratory tests on herring. He found that the peak suspended solids concentrations measured in the Oakland study were well below concentrations demonstrated to affect embryo development and hatching, well below most but not all of the concentrations reported to affect larval survival, and within the range in which one study found enhanced larval feeding.

Recent projects at the Richmond Long Wharf and Redwood City shipping channel provide information on resuspension of sediment in the Bay by ship traffic and by a knockdown, that is, mechanical smoothing of the bottom with an iron beam (Weston Solutions and USACE Research and Development Center, personal communication). At Richmond, a study that had been planned to monitor suspended sediments during a dredging event instead provided opportunistic acoustic, optical, and gravimetric measurements during the berthing of a deep draft vessel.

Plumes were generated during vessel berthing, a result of the vessel propeller, multiple tug boats, and/or displacement of water creating sheer stress against the bottom substrate, and lasted at least 75 minutes (Figure 3-3), which was the length of time in which measurements were made. The maximum lateral extent of the plume (across tidal flow) was approximately 350 meters.

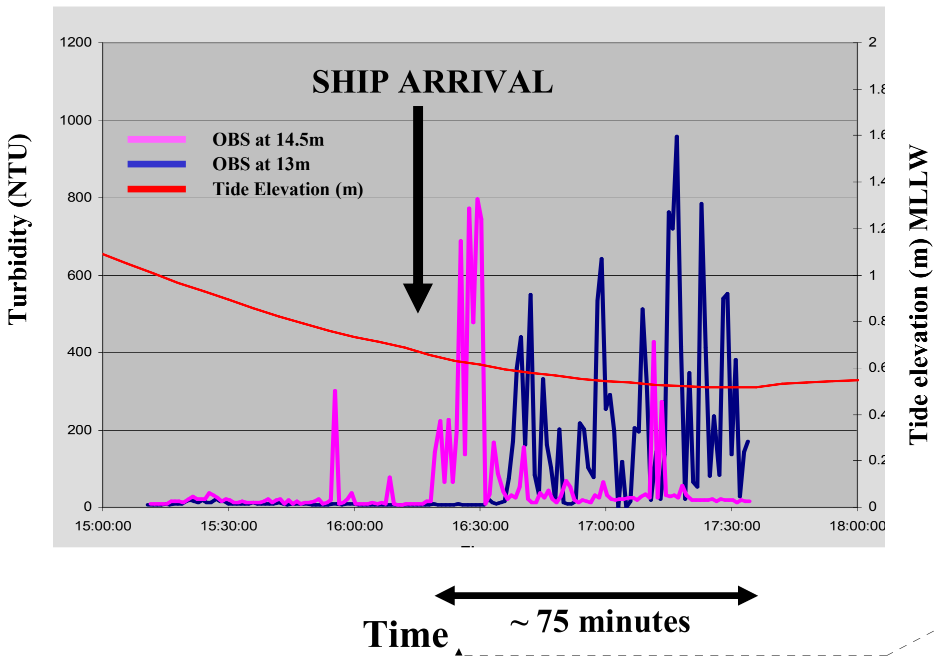

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Figure 3-3. Turbidity as a measurement of optical back scatter (OBS) at Richmond Long Wharf before and after deep draft (~39 ft) vessel arrival (courtesy of Weston Solutions and US Army Engineer Research and Development Center)

In contrast, the knockdown study at the Redwood City shipping channel characterized a plume that was relatively small and decayed fairly rapidly. The perpendicular extent of the dredge plume was approximately 20 meters from the closest side of the channel, extending out into the channel. Maximum suspended solids concentrations were approximately 200 mg/L and were localized in the area around the knockdown bar (Figure 3-4). Plume decay was rapid, about 3-5 minutes from when the barge passed until the barge reached 220 meters from the sampling point.

These two studies suggested that resuspension of sediments from ship traffic may be greater than and occur more frequently than resuspension during dredging. Further, the material suspended during docking may be more likely to be transported to the wharves and pilings on which herring spawn.

Several other studies from San Francisco Bay have also measured suspended solids concentrations at various shipping channels during dredging. In a study of dredge overflow, bottom plumes extended vertically up to three meters from the bottom and surface plumes were present (USACE 1976). The bottom and surface plumes merged at a distance of approximately 100 meters. The plumes were approximately 300 meters long at the surface and 450 meters long at the bottom, existing up to 700 meters downstream of the dredge. Suspended solids concentrations during hopper-dredge operations at several locations were variable, with concentrations at Richmond Harbor ranging from an average of 33 mg/L (5 meters depth) to 145 mg/L (10 meters depth) along the centerline of the dredge. At Mare Island, bottom (10 meters depth) suspended solids concentrations reached a maximum of 2600 mg/L (average 337 mg/L) at a distance of 50 meters. The authors speculated that the high suspended sediment concentrations at Mare Island could have been due to low salinity and subsequent reduced flocculation.

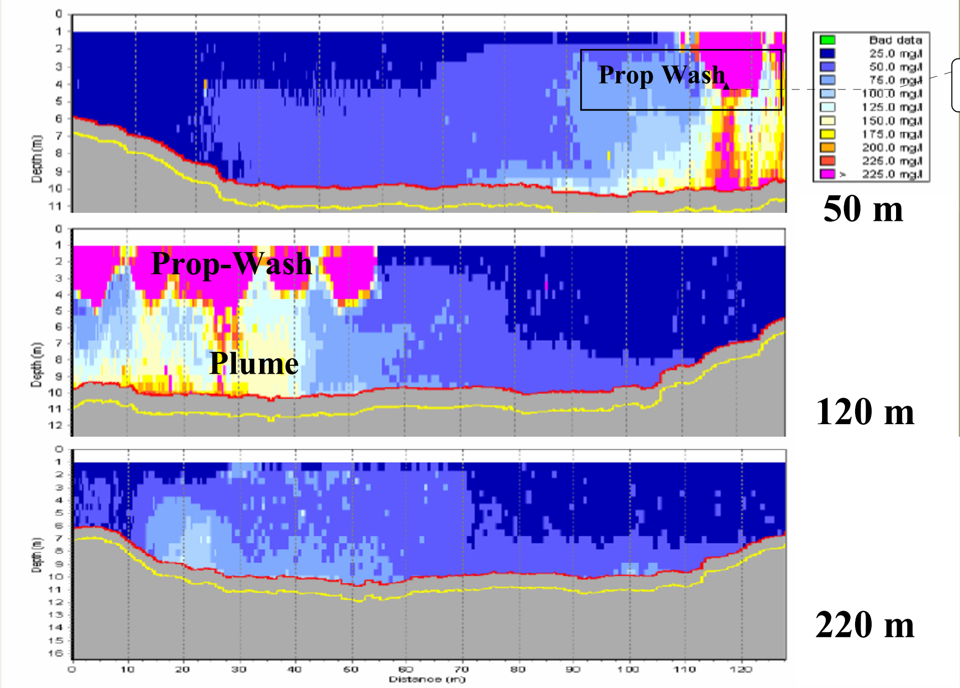

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Figure 3-4. Suspended solids concentrations during knockdown study at Redwood City shipping channel (courtesy of MEC/Weston and Douglas Clarke, USACE-WES)

Type of dredge. The quantity of sediment resuspended during dredging operations depends upon the type of dredge used, the water body in which the operation takes place, and the type of material being dredged (Herbich and Brahme 1991, Wilber and Clarke 2001). Operator training and performance can also affect the amount of material that is resuspended.

Mechanical dredges generate higher suspended solids concentrations than hydraulic methods. In a Boston Harbor study, a conventional bucket dredge generated higher turbidity and greater suspended sediment concentrations than cablearm or enclosed buckets (Welp *et al.* 2001). With the conventional bucket, there was increased turbidity throughout the nearfield water column. Farfield suspended sediment concentrations were also somewhat higher. A cutterhead operation generated 150 mg/L total suspended solids in a plume 0-100 m in length. Bottom concentrations were about 1000 mg/L. Turbidity from a hydraulic clam dredge used in Chesapeake Bay decreased exponentially with time. The initial decrease was more rapid as coarser sediments settled out of the water column (Ruffin 1998). The average time for turbidity to return to 95% of background levels after dredging ended was 2.9 hours in water greater than 1.0 meters depth.

Salinity. Increasing salinity tends to neutralize repulsive forces between clay particles and increase flocculation of these particles. Salinities as low 1-5‰ can be sufficient to induce flocculation and reduce turbidity (Herbich and Brahme 1991, Burban *et al.* 1989). Percent organic material also influences flocculation.

Type of material. Suspended sediment concentrations also tend to be higher when particle size of the material being dredged is smaller (Herbich and Brahme 1991). Much of the sediment in San Francisco Bay is fine, composed of more than 40% fine material (Figure 3-5).

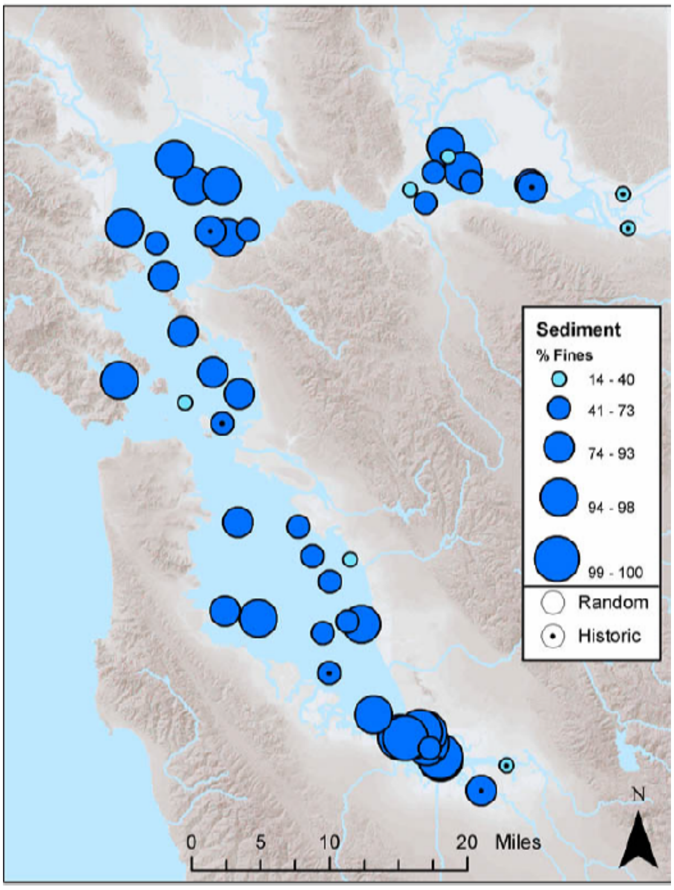

Figure 3-5. Percent fine fraction in sediments from 2002 RMP monitoring stations. Random = stratified random sampling; Historic = non-randomly selected sites; % fines = sediment < 63 µm

Operator performance. In a planned study of hopper overflow, a hopper dredge operated 10–15 minutes beyond the filling point resulted in maximum average total suspended solids concentrations of 800 mg/L above background concentrations (McLellan 1989). The plume extended to 7000 feet beyond the dredge at concentrations of up to 300 mg/L below the 75% depth level. Concentrations above background levels persisted for approximately 40 minutes after the overflow activity ceased.

Comparison to natural conditions. While increased turbidity and suspended solids can be detected in dredging operations, those increased levels can be minor in comparison to natural events. For the Bay as a whole, Andy Jahn (Port of Oakland, personal communication) has calculated that the volume of material dredged per year is approximately 2% of the volume of material resuspended by natural forces and of that 2%, about 1-2% is suspended during dredging. Bohlen *et al.* (1979) also noted that storms affect greater areas and occur more frequently than dredging operations. In a study of suspended material downstream from a bucket dredge operating in New London, Connecticut, they found that about 1.5-3% of the volume of the bucket was lost to the water column. Maximum suspended sediment concentrations were 200-400 mg/L, about two orders of magnitude above background. Within 200 m, concentrations were within one order of magnitude higher than background, and within about 700 m, concentrations approached background levels. In comparison, a storm event increased suspended sediment concentrations by at least a factor of two throughout the estuary.

Schoellhamer (2002) compared suspended sediment concentrations approximately 1.5 km from a disposal site during a dredged material disposal event in San Pablo Bay to natural estuarine resuspension processes and found that even during disposal events, natural forces controlled suspended sediment concentrations. Suspended sediment concentrations were not correlated with the volume of dredged material being disposed; rather, wave-induced resuspension had the greatest effect on suspended sediments. In Hillsborough Bay, Florida, ship movements were also found to cause resuspension (Schoellhamer 1996, Steuer 2000).

Schoellhamer also found no effect of dredged material disposal at the Alcatraz disposal site on suspended solids concentrations at San Francisco Pier 24 at the western end of the Bay Bridge (Figure 3-6). While there was no obvious relationship between the amount of material disposed of at the Alcatraz disposal site and total suspended solids, there was an obvious correlation between Delta outflow and suspended solids in near-bottom waters.

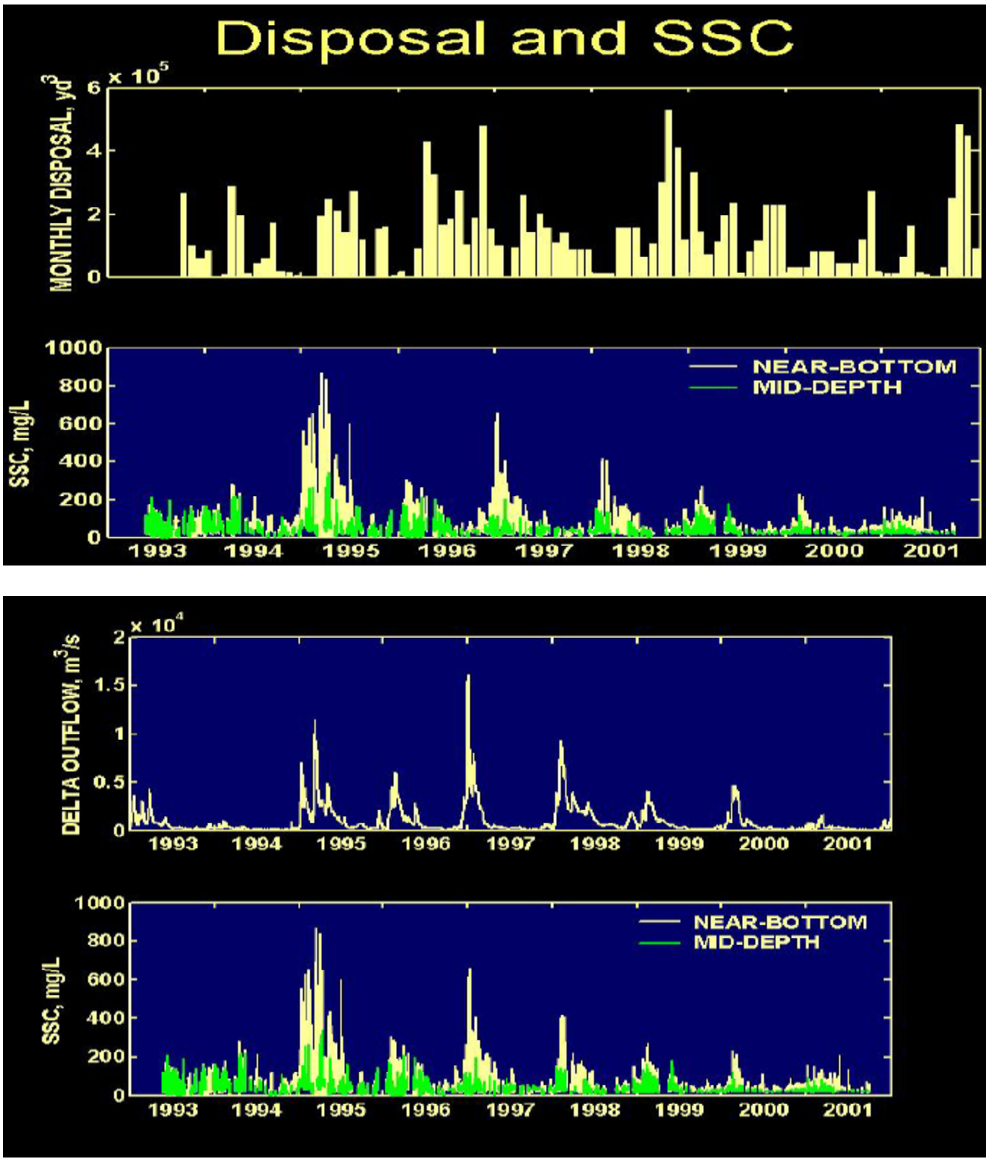

Figure 3-6. Top: Monthly dredged material disposal at Alcatraz disposal site, and suspended solids concentrations at Pier 24 in San Francisco, near the Oakland Bay Bridge; measurement is a farfield effect; Bottom: Delta outflow and suspended solids concentrations at Pier 24; measurement is a nearfield effect (courtesy of Dave Schoellhamer)

3.2 Reduced Oxygen Concentrations from Dredging

One issue of concern noted in the letter providing the rationale for the environmental work window was the possibility of reduced oxygen concentrations in the water column. Nightingale and Simenstad (2001) considered this possibility in their review of issues associated with dredging in Washington State. They concluded that the existing literature did not support the hypothesis that dredging, even of anoxic sediments, significantly lowered the dissolved oxygen levels in the surrounding waters. They cited, for example, Houston *et al.* (1990 as reviewed by Nightingale and Simenstad 2001), who found that dredging in the Haverstraw Bay area of the Hudson River Estuary slightly elevated the turbidity and reduced dissolved oxygen saturation, but saturation increased when the dredging operations ceased, and Lunz *et al.* (1988) who reported a "worst case" dissolved oxygen reduction as no more than 0.1 mg/L with a suspended solids load of 500 mg/L. While Nightingale and Simenstad also cited research documenting greater changes in dissolved oxygen concentrations (Table 3-2), they dismissed such measurements as being extremely limited in spatial and temporal extent.

Dredging studies from the 1970s in San Francisco Bay showed that dredged material disposal produced greater reductions in dissolved oxygen concentrations than dredging itself (USACE 1976). In maintenance dredging operations occurring in the shipping channels of Mare Island Strait, Pinole Shoal, Richmond Harbor, and Oakland Harbor using a suction hopper dredge, dissolved oxygen concentrations were reduced by a maximum of 4 mg/L at the sediment-water interface and returned to background concentrations within eight minutes. Surface dissolved oxygen concentrations were reduced by up to 2 mg/L for a duration of approximately two minutes. Reductions in dissolved oxygen concentrations decreased with increasing distance from the dredge and were at ambient concentrations (8-9 mg/L) within 100 meters downstream of the dredge. In the recent Oakland harbor dredging study dissolved oxygen levels fell below 5 mg/L during only one of the transects. This transect occurred during a flood tide. For all other transects dissolved oxygen levels were equal to or greater than 5 mg/L (MEC-USACE Research and Development Center, 2004). The water quality objective established to protect biota in the Bay (South of the Carquinez Bridge) is 5 mg/L (SFBRWQCB, 1995).

Concentrations of dissolved oxygen in San Francisco Bay are generally high, even in lower South Bay, which has the lowest long-term summer mean concentrations of any portion of the Bay (Figure 3-7). However, concentrations of dissolved oxygen in enclosed embayments where most marinas are located may be lower than levels at open water dredging sites, and estimates of dissolved oxygen declines from open water dredging sites may not be comparable to those in enclosed marinas (Brenda Goeden, personal communication). Currently, there is no local information on the effects of dredging on dissolved oxygen near enclosed marinas, and a study has been proposed by the LTMS science group.

Table 3-2. Dissolved oxygen measurements at dredge sites (Nightingale and Simenstad 2001)

Location	Dredge Type	Dissolved Oxygen Effects	References
Hudson River, New York	Bucket	Less than 0.2 mg/L reduction in the lower water column	Lunz *et al.* 1988; Houston *et al.* 1990
Grays Harbor, Washington	Cutterhead	Periodic reductions of 2.9 mg/L	Smith *et al.* 1976
Oregon tidal slough	Hopper	1.5-3.5 mg/L reduction in the lower water column at slack; 2 mg/L increase at flood tide	USACE 1982
Coos Bay, Oregon	Hopper	Minimal to no change	Slotta *et al.* 1973

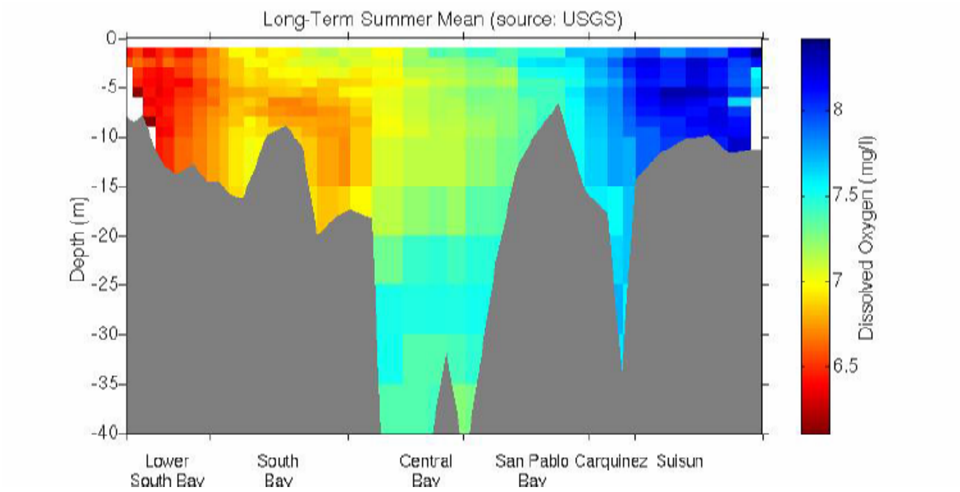

Figure 3-7. Long-term mean summer dissolved oxygen throughout the water column in embayments of San Francisco Bay

3.3 Contaminants from Dredging

As described in Section 2.7, metals and organic pollutants are found throughout San Francisco Bay and particularly in some of the coastal embayments that require regular dredging. Specific contaminants of concern in San Francisco Bay include mercury, PCBs, PAHs, and pesticides, which have a legacy of historic inputs from various sources. Potential effects of resuspension of contaminants during dredging on Pacific herring was one of the concerns that led to development of the environmental work window.

Much of the information on resuspension of contaminants during dredging comes from studies of severely contaminated areas. For example, in a remediation study at an East San Francisco Bay Superfund site, at which DDT had been prepared and packaged for sale, dredging with a clam shell dredge mobilized DDTs into the area and resulted in increased contaminant concentrations in some resident crab, mussel, and anchovy samples (Weston *et al.* 2002). In samples taken four months after dredging, DDT concentrations in anchovy tissues were 76 times higher than before dredging. At 16 months, body burdens of most of the organisms were lower than the 4-month samples but many remained elevated above pre-dredging levels. Similarly, PCB-contaminated sediment removed by a vacuum dredge in Norway resulted in elevated PCB concentrations in mussels and semi-permeable membranes (SPMs) used to simulate organisms (Voie *et al.* 2002).

Twenty-eight day laboratory bioaccumulation experiments conducted in coordination with the Oakland Harbor Deepening Project (42 feet) found low bioavailability of contaminants from suspended and bedded sediments from Inner and Outer Oakland Harbor (McFarland *et al*. 1994). There were some exceptions: chromium accumulated in clams, mussels, and sanddabs, and tributyl tin accumulated in clams in tests run with Inner Harbor sediments. Cadmium and chromium accumulated in clams and mussels in tests run with Outer Harbor sediments. Concentrations of contaminants were generally higher in mussels and clams than in fish. For most of the exposures, there was no significant difference between accumulated contaminant concentrations from bedded sediments or suspended sediments.

In a freshwater, riverine remediation site, dissolved and particulate PCB concentrations were consistently higher at a site downstream from dredging when compared to an upstream site (Figure 3-8; Steuer 2000).

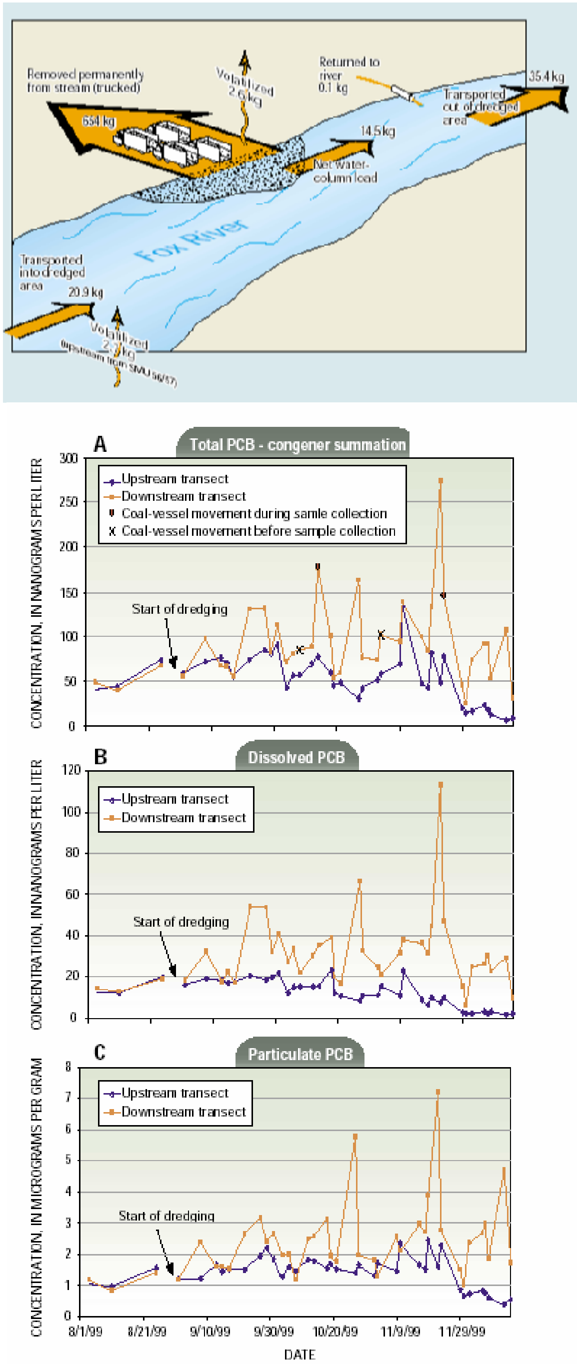

Figure 3-8. Mass flux of PCBs in the Fox River during dredging operations (Steuer 2000)

The degree to which contaminants dissolve or attach to sediment particles and the size of sediment particles affect the degree to which contaminants are introduced to the environment by dredging. PCBs, PAHs, and pesticides, which sorb to fine-grained sediments in the water column, can remain suspended in the water column or can redeposit onto the sediment bed, depending upon sediment particle size (Domagalski and Kuivila 1993, Schnoor 1996). Dissolved or weakly adsorbed contaminants are more bioavailable (reviewed by Eggleton and Thomas 2004). How contaminants desorb from resuspended sediments to the dissolved phase depends on the particle/floc size and density distributions, type of water, and organic content of the sediments (McFarland *et al*. 1989, Schwarzenbach *et al.* 1993).

A computer model simulating release of contaminants from a 1-hour dredging operation found that the partitioning of a chemical between the water and suspended particulate material was most dependent on the solubility of the chemical (van Oostrum and Vroege 1994). In a laboratory study, sediment from Lavaca Bay, Texas was mixed with filtered seawater in a laboratory experiment to measure potential mercury release during resuspension (Bloom and Lasorsa 1999). Concentrations of dissolved mercury increased 1 hour after resuspension and remained elevated after 24 hours. They predicted that in the field, most of the mercury would re-adsorb to the high suspended particulate load.

3.4 Noise from Dredging

Sound intensity, periodicity, and spectra vary by type of dredge (reviewed by Clarke *et al.* 2002). Bucket dredges have repetitive sequences of sounds, including winch, bucket impact, bucket closing and bucket emptying. Cutterhead dredges have relatively continuous sounds made by the cutterhead rotating through the substrate. Hopper dredges produce a combination of sounds from the engine/propeller and from the draghead in contact with substrate.

The transmission of underwater sound is dependent upon the type of substrate, ambient suspended sediment loads (which tend to scatter and attenuate sound), geomorphology of the waterway, hydrodynamic conditions, condition of the equipment, and the skill of the dredge operator. The Clarke *et al.* (2002) review found that sound of bucket impact with the substrate was at the limit of detection by a low-noise hydrophone and hydrophone audio amplifier at 7 km from the impact point. Cutterhead sounds peaked at 100-110 dB in the frequency range of 70-1000 Hz and were inaudible at ~500 m from the source. The hopper dredge sound peaked at 120-140 dB and fell within a frequency range of 70-1000 Hz. In a study at Cook Inlet, Alaska, the sound of the bucket striking a mixed sand and/or gravel substrate was the most intense sound generated from all aspects of bucket dredge operations and was measured up to 3000 meters from the dredging site (Dickerson *et al*. 2001). Peak sound pressure levels were 124.0 dB re 1 μPa-m at a peak frequency of 162.8 Hz measured at 150 meters from the bucket strike location, 50.8 dB re 1 µPa-m above peak ambient conditions.

Sound pressures for a 2001 Fisheries Impact Assessment to determine potential fish effects of pile driving for the San Francisco-Oakland Bay Bridge construction were 29 times higher than the Cook Inlet dredge measurement (based on calculation from Connor *et al.* 1999). Even accounting for attenuation, the root mean square impulse (a measure of sound impulse) during pile driving (199-201 dB re 1 µPa-m) was more intense than sound from dredging operations (124.0 dB re 1 µPa-m).

4. Conclusions

The goal of this white paper is to identify information gaps and potential research that could be used to better assess the potential for impacts of dredging on Pacific herring in San Francisco Bay. During development of the paper, the expert panel met twice to review existing data and to suggest potential further research. Scientists, regulators, dredging permittees, the fishing community, and dredge operators participated in one or both meetings. The process identified a variety of information gaps and recommended research on knowledge of the ecology of Pacific herring in San Francisco Bay, about dredging operations in the Bay, about the factors that affect the Pacific herring population, and about the relative effects of dredging (Figure 4-1).

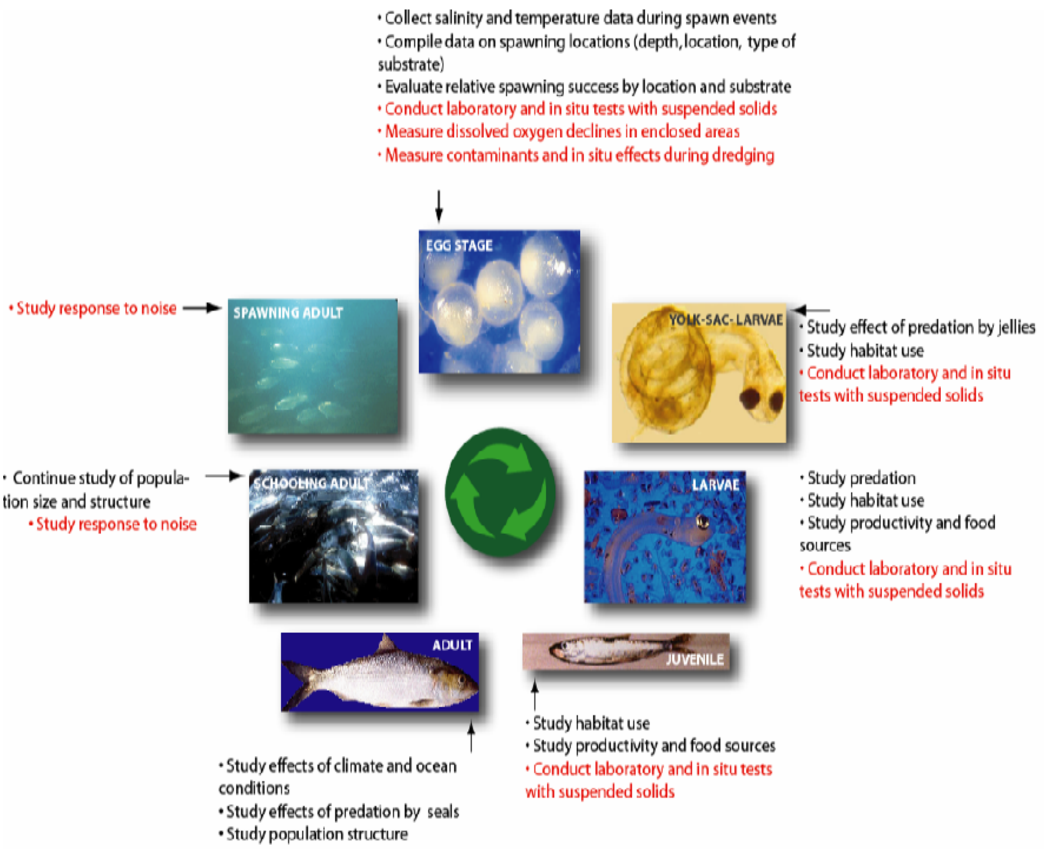

Figure 4-1. Proposed research on Pacific herring (General studies are noted in black; areas specifically related to dredging are in red)

The expert panel and other participants in the development of this paper did not agree on every priority. Some scientists noted that current research suggests that effects of dredging on Pacific herring may be minimal, because increases in suspended solids during dredging are spatially small, short-lived, and insignificant in comparison to natural conditions. They also noted that while all Bay sediments have some degree of contamination, the most consistently toxic sediments are located upstream from herring spawning areas, and especially contaminated sediments are treated with extra protection during dredging. On the other hand, other scientists pointed out that the Pacific herring population in San Francisco Bay is depressed and that any stress, even a minor one, could adversely affect the population. Several scientists suggested that the environmental windows may be aimed at the wrong life stage, that larvae and juveniles may warrant equivalent or even greater protection than eggs.

4.1 Pacific Herring in San Francisco Bay

Although DFG has intensively studied Pacific herring in San Francisco Bay for more than 30 years, some of the available data have not been synthesized or published, and other potentially useful information has not been collected. For example, DFG has extensive information on spawning waves and spawn deposition, but the relative success of spawning on different substrates in frequently and infrequently used areas is not known. Further, there is little information on distribution, abundance, or ecology of herring larvae and juveniles in the Bay. Even the length of time in which larvae remain in the vicinity of the spawning area is unknown. While the current environmental window is designed specifically to protect spawning behavior and egg viability, the panel suggested that larval and juvenile stages may be equally or more at risk, and additional information about those stages would be warranted.

4.2 Dredging in San Francisco Bay

Similarly, detailed information about dredging locations and depths, the type of dredge used, the amount of material removed, the physical and chemical attributes of the material, and preferred and acceptable dredging schedules exists but is not readily available in one location.

Together, more detailed information about herring spawning and dredging in the Bay could be used to develop a more complex management strategy than the current environmental work window. For example, one participant has suggested development of a simple matrix of spawning sites and dredging sites. Dredging in areas that are frequently used for intense spawning, for example, Richardson Bay, would be of greatest concern, particularly during the spawning season.

4.3 Factors that Affect Herring Populations

Available information suggests that fishing, climate, food resources, predation, habitat, suspended solids, contaminants, and noise may affect the Pacific herring population in San Francisco Bay (Table 4-1), but for most of these factors, there is limited information to suggest effects, at least not on the population level. Further understanding of herring life history and the potential impacts to the population could improve the management of the species and improve our understanding of which life stages are most vulnerable to adverse impacts.

Information from DFG indicates that stock size, as estimated from the spawn surveys, has been low since the late 1980s. The low levels may be related to fishing pressures during a period in which DFG estimates of spawning biomass may have been elevated due to survey techniques. This period of seeming decline also followed an El Niño event, a factor known to affect the herring population in the Bay. How the sustained reduced population relates to potential effects of dredging (or other factors) is not clear. Absolute effects could be smaller, because fewer individuals would be affected, spawning areas could be smaller, and spawning duration could be shorter. Relative impacts, however, could be greatest when the populations are small, because a higher proportion of individuals could be affected by deleterious impacts.

It is known that contaminants can affect individual herring, but the effects on the population are unknown. Most studies have focused on PAHs. Potential effects of other contaminants, such as PCBs, pesticides, dioxins, and mercury, are unknown. Since there are multiple contaminants in the sediments of San Francisco Bay, a multi-contaminant approach to toxicity could more accurately reflect the natural conditions. Longer-term contaminant effects studies would be important in assessing mortality beyond the duration of acute toxicity testing.

Table 4-1. Recommendations for studies concerning factors that affect Pacific herring

Factors that Affect Pacific Herring	Status in San Francisco Bay	Information Gaps and Recommendations
Fishing	A known factor affecting Pacific herring populations. DFG has determined that targeted exploitation rates were exceeded in some years between1989-2002.	Continued examination of trends in population size and year-class structure is necessary to determine the status of the resource and the necessary level of protection.
Environmental Factors	Environmental factors are known to affect Pacific herring populations. DFG has noted that Post El Niño years typically have lower spawning biomass.	Study of temperature and salinity within the Bay and conditions outside the Bay could further elucidate the status of the population. Studies of hake, sardine, and anchovy could provide models for further study.
Food Resources and Competition	San Francisco Bay is relatively unproductive. Introduction of exotic species has led to smaller zooplankton species, which may be less valuable food.	Greater information on productivity and zooplankton populations in herring spawning and nursery areas is needed. Changes in response to salt-marsh reconstruction in the South Bay should be monitored.
Predation	Predation on larvae by jellies is important in other areas. Predation on adults by mammals may be important; the coastal harbor seal and sea lion populations have increased since passage of the Marine Mammal Protection Act of 1972.	Additional studies could document effect of predation by jellies on larvae. DFG data could document geographic and temporal relationship between harbor seals and herring population size and spawning locations.
Habitat	Much spawning occurs on manmade structures. Eelgrass beds cover 1% of the Bay, possibly reduced from the historic extent.	Relative success of spawning in natural locations compared to wharves and pilings and in frequently and infrequently used sites would be valuable. Field studies of habitat use and ecology of larvae and juveniles could affect the rationale for an environmental work window. Depth and width of spawning areas could also be explored.
Suspended Solids and Sedimentation	Suspended solids levels in the Bay are naturally high, but not at levels that presumably affect spawning behavior, egg viability, or feeding.	Laboratory studies could be conducted immediately and should use realistic concentrations to examine effects on eggs and larvae. These results should be compared to information on suspended solids concentrations in spawning areas.
Contaminants	Most toxicological studies have been in response to the *Exxon Valdez* oil spill rather than to routine urban pollution. Sediment contaminants in San Francisco Bay often occur in highest concentrations in shallow areas. Egg deposition onto creosoted pilings may be of concern.	Relative success of spawn on creosoted pilings vs. natural habitats should be studied.
Noise	Pacific herring have been documented to respond to and to avoid sounds. Pile-driving in Oakland was associated with mortality.	Additional information on responses to sound could be collected.

4.4 Effects of Dredging on Herring

To date, laboratory experiments have shown little or no effect of suspended sediments on life stages of Pacific herring, but there remain some questions, and LTMS has already planned for additional laboratory tests. In a dredging field study using a bucket dredge in Oakland Harbor a maximum suspended sediment concentration was 275 mg/L (MEC-USACE Research and Development Center, 2004), less than any effects level in the literature surveyed except for possible avoidance by juveniles. Also, available information indicates that levels of suspended solids released during dredging are not significant in comparison to those suspended by natural events such as storms or other human activities such as large vessel movement. Further, some panel members have suggested that dredging during the winter, when concentrations of suspended solids are naturally at their highest, would be unlikely to be detected by or affect herring. Others have suggested that any additional increase in suspended solids during turbid periods could be harmful. A comparison of sources, geographic extent, and duration of suspended material in the Bay from dredging, ship movements, and other forces would be useful in determining the relative effects of these stresses.

Dissolved oxygen appears not to be severely reduced by dredging, and noise during dredging is not unlike other routine noise in busy harbors. However, dissolved oxygen declines in enclosed areas may be greater than those that have been measured in open waters, and the LTMS science group has proposed studying that possibility.

There remains uncertainty about the effects of dredging on contaminant release from suspended sediments, particularly if the material to be dredged is highly contaminated. One suggestion for a future research project is to transplant herring eggs to an active dredging site to measure potential effects on egg survival and embryonic development. In conjunction with this experiment, measurement of the bioavailable portion of sediment contaminants resuspended by dredging would also be useful. The Dredged Material Management Office requires that the toxicity of dredged material be evaluated to ensure that there are no acute contaminated-related effects of disposal. Information from those tests could also be used to evaluate the potential for effects at the dredging site.

Table 4-2. Recommendations for studies concerning the effects of dredging operations

Effects of Dredging Operations	Status in San Francisco Bay	Information Gaps and Recommendations
Suspended Solids and Sedimentation	Peak concentrations of suspended solids during dredging appear to be lower than those associated with effects on egg viability. Storms and the spring/neap tidal cycle may have a greater and longer enduring effect on suspended solids concentrations.	Laboratory studies could be conducted immediately and should use realistic concentrations to examine effects on eggs and larvae. Field experiments in which eggs were transplanted to dredging areas could also be conducted. Differences in dredging operations of varying magnitude, in for example a marina versus a shipping channel, should be compared.
Reduced Oxygen Concentrations	Dissolved oxygen concentrations appear to be minimally affected by dredging operations.	Spatial and temporal extent of effects should be defined.
Contaminants	Contaminant concentrations increase in biota following dredging of extremely contaminated sites.	Measurements of bioavailable contaminants during dredging experiment should be made.
Noise	Noise from dredging operations is not significantly different from routine conditions in an urban estuary.	Studies of responses of schooling adults to noise associated with dredging could be conducted.

4.5 Priorities

A clear majority of panel members and participants agreed that the priorities for continued research into the possible effects of dredging on Pacific herring in San Francisco Bay should focus on suspended solids and contaminants.

The panel recognized that many of the recommended studies could take years and that we will never completely understand the potential effects. Therefore, it is important for LTMS to develop short-term, practical solutions to minimize the conflict between dredging and resource management. This white paper accomplishes the LTMS goals to develop a peer-reviewed summary of the state of knowledge and uncertainties regarding the effects of dredging on herring, with the intention that LTMS could then convene its stakeholders to determine whether there are more effective ways to manage dredging and protect the Pacific herring population than the current environmental work window.

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