# Mercury in the San Francisco Estuary

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## I Introduction

### *A Purpose and Scope*

Ever since the recognition of mercury as an environmental problem, San Francisco Estuary has been an active area of mercury research. It is little wonder that this is so: the estuary is in the middle of a region of mercury mineralization and historic mercury mining, and it is downstream of an area of historic gold mining where millions

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of kilograms of mercury were used. It is also a heavily urbanized area that once featured chloralkali facilities and numerous shipyards potentially contaminated with mercury-based paints. In addition, it is a drainage area for rich agricultural regions that may have seen substantial environmental applications of mercury insecticides and fungicides. In this review, we present a survey of literature on mercury contamination and biogeochemistry focusing on San Francisco Estuary. Our intent is to stimulate scientific questions addressing mercury contamination in this and other estuarine systems, as well as to describe the restoration and management efforts that accompany mercury-contaminated sites.

## *B Overview of the Problem*

Before presenting work specific to mercury contamination in San Francisco Estuary, an overview of the environmental mercury problem and mercury chemistry is appropriate. There are many valuable reviews on this wider topic, with focuses on toxicological (Clarkson and Magos 2006), biogeochemical (Benoit et al. 2003; Fitzgerald and Lamborg 2003; Fitzgerald et al. 2007; Ravichandran 2004; Ullrich et al. 2001), ecological (Wiener et al. 2003), and microbiological aspects (Barkay et al. 2003).

Mercury is an environmental and human health concern largely because of the formation of methylmercury, particularly monomethylmercury (MMHg), which is bioaccumulated and biomagnified to toxic concentrations in higher trophic level organisms, including birds (Schwarzbach et al. 2006) and mammals (Wiener et al. 2003). It is a neurotoxin for humans, and effects have been noted in populations consuming fish (Clarkson and Magos 2006). In estuarine systems, sediments are a primary area of MMHg production (Mason et al. 2006). Sulfate-reducing bacteria are thought to be the principal methylators of mercury in anoxic estuarine sediment (Compeau and Bartha 1985), although iron-reducing bacteria have recently also begun receiving scrutiny (Kerin et al. 2006). The production of MMHg is, therefore, controlled by factors influencing the distribution of mercury between abiotic and biotic compartments, such as sulfur chemistry and organic matter, and by factors that control microbial activity, such as temperature and the availability of suitable organic matter for cellular respiration (Gilmour and Henry 1991; Hammerschmidt and Fitzgerald 2004; Heyes et al. 2006; King et al. 2001). Methylmercury produced in sediment that is exported to the water column can be bioaccumulated by phytoplankton or other organisms (Pickhardt and Fisher 2007) and biomagnified to higher trophic levels (Lawson and Mason 1998).

## *C Environmental Setting of San Francisco Estuary*

An understanding of the setting of San Francisco Estuary is essential as a backdrop for this review. The monograph *San Francisco Bay: The Urbanized Estuary* is an older, but excellent description (Conomos 1979), as is the more recent *San Francisco*

*Bay: The Ecosystem* (Hollibaugh 1996). In addition, articles are available on the characteristics and circulation patterns in the estuary (Conomos et al. 1985), temporal fluctuation and time scales of variability of estuarine parameters (Cloern and Nichols 1985; Thomson-Becker and Luoma 1985), and anthropogenic modification of the estuary over time (Nichols et al. 1986). Some recent studies have covered water circulation, salinity, and nutrients (Kimmerer 2002; Monismith et al. 2002; Smith and Hollibaugh 2006); suspended sediment (Ganju et al. 2005; McKee et al. 2006; Ruhl et al. 2001; Schoellhamer 2002); organic carbon (Lesen 2006; Murrell and Hollibaugh 2000; Stepanauskas et al. 2005); marsh formation (Watson 2004); and sedimentation (Foxgrover et al. 2004; Jaffe and Foxgrover 2006; Jaffe et al. 1998).

San Francisco Estuary is a truly unique setting (Fig. 1). It is a natural, semienclosed body of water created by right-lateral movement on the San Andreas fault system (Hedgpeth 1979). It is the largest estuary on the California coast and is heavily urbanized (Nichols et al. 1986). Its circulation is controlled by tidal currents and freshwater flow, which is dominated by the distinctly Mediterranean climate in the region—dry summers and wet winters (Kimmerer 2002). San Francisco Estuary can be divided into two geochemically distinct subestuaries, the northern and southern reaches, which join in the Central Bay and connect to the Pacific Ocean via the Golden Gate (Flegal et al. 1991). The system has further been divided into six hydrographically distinct regions: Tributaries, Southern Sloughs, South Bay, Central Bay, Northern Estuary, including San Pablo Bay and Suisun Bay, and River-Delta (Conaway et al. 2007). Ninety percent of the annual freshwater inflow to the estuary enters via the northern reach through the delta formed by the convergence of the Sacramento-San Joaquin drainage basins, which includes most of the Coast Ranges, the Central Valley of California, and the western Sierra Nevada (Conomos et al. 1985). The Napa and Petaluma Rivers, which also drain to the northern reach, provide local drainage from the Coast Ranges, but their discharges are relatively small in comparison. In contrast, the southern reach receives only a small amount of freshwater input (<10% of the total freshwater input to the estuary), mostly from the Guadalupe River, Coyote Creek, and other small tributaries that locally drain the Coast Ranges and the Santa Clara Valley. Onto this physically and chemically complex system is superimposed an ecologically and biogeochemically complex mercury contamination issue, which has been the focus of many studies reviewed here.

## II Issues Related to Mercury Contamination in San Francisco Estuary

Concerns about mercury in San Francisco Estuary center on human health and ecological effects on birds. The San Francisco Bay Regional Water Quality Control Board (SFRWQCB), which is tasked with the preservation of beneficial uses of the estuary, has determined that the estuary is impaired for mercury, in part because of the reported concentrations of mercury in fish tissue and bird eggs (SFRWQCB 2006). Studies on fish and ecotoxicological effects on birds both support this regulatory statement and highlight concerns of mercury toxicity.

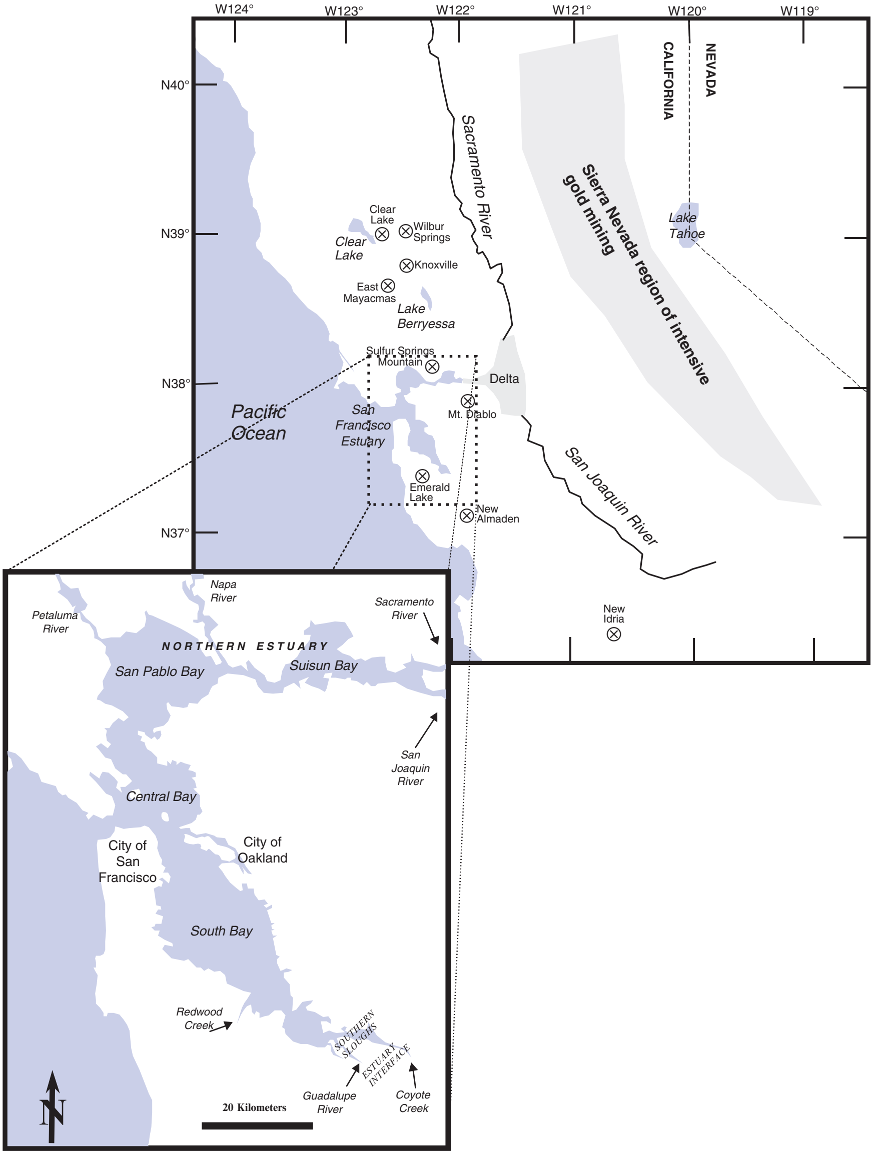


**Fig. 1** Regional map of San Francisco Estuary, California, with inset detail. Regional map shows area where intensive gold mining in the foothills of the Sierra Nevada occurred. Locations of large mercury mining districts in the San Francisco Estuary watershed are shown with an "⊗" symbol. Inset shows the estuary and its larger tributaries. Distinct hydrographic regions are Rivers (the confluence of the Sacramento and San Joaquin), Northern Estuary, Central Bay, South Bay, the Southern Sloughs, and Estuary Interface

## A Human Health

Consumption of mercury-contaminated fish from the estuary is the issue most relevant to human health. Accordingly, recent studies of mercury in fish in San Francisco Estuary (Davis et al. 2002; Fairey et al. 1997; Greenfield et al. 2005) have focused on concentrations and spatial and temporal trends in those concentrations in various fish species. The range of concentrations in several species are summarized in Table 1. Fish mercury concentrations can exceed regulatory standards in leopard shark, striped

**Table 1** Survey of total mercury ($Hg_T$) and methylmercury (MeHg) concentrations (μg $g^{-1}$) in organisms from San Francisco Estuary

| Species | Tissue | $Hg_T$ (μg $g^{-1}$), range (mean), wet weight | MeHg, (μg $g^{-1}$), wet weight | Notes |
|---|---|---|---|---|
| **Fish**[a,b] | | | | |
| California halibut (*Paralichthys californicus*) | Muscle | 0.20–0.36 | | |
| Jacksmelt (*Atherinopsis californiensis*) | Muscle | 0.068–0.17 (0.09) | | |
| Leopard shark (*Triiakis semifasciata*) | Muscle | 0.28–1.3 | | |
| Shiner surfperch (*Cymmatogaster aggregata*) | Muscle | 0.068–0.42 | | |
| Striped bass (*Morone saxatilis*) | Muscle | 0.15–0.55 | | |
| Sturgeon (*Acipenser transmontanus*) | Muscle | 0.25–0.30 | | |
| White croaker (*Genyonemus lineatus*) | Muscle | 0.069–0.41 | | |
| **Birds** | | | | |
| California clapper rails *Rallus longirostris obsoletus*)[c] | Egg[d] | 0.11–2.5 | | MeHg averaged 95% of total in subset analyzed |
| Canvasbacks (*Aythya valisineria*)[e] | Liver | ND–9.4[f] | | |
| Greater scaup (*Aythya marila*) | Liver | 1.8–20[f] | | |
| Lesser scaup (*Aythya affinis*) | Liver | 1.1–9.9[f] | | |
| Surf scoters (*Melanitta perspicillata*) | Liver | 5–21[f] | | |
| Ruddy ducks (*Oxyura jamaicensis*) | Liver | 2–7[f] | | |

(continued)

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