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Mercury Strategy for the Bay-Delta Ecosystem: A Unifying Framework for Science, Adaptive Management, and Ecological Restoration

by

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Final Report to the California Bay Delta Authority

for

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the Association of Bay Area Governments

and

the University of Wisconsin-La Crosse

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EXECUTIVE SUMMARY

This document outlines a strategy for integrated mercury investigations linked to restoration and adaptive management of the San Francisco Bay and Sacramento-San Joaquin Delta ecosystem (termed the Bay-Delta ecosystem and defined as the combined watershed, Delta, and Bay). Ecosystem restoration and management of the Bay-Delta ecosystem are complicated by mercury contamination from historic mining sites in the Sacramento and San Joaquin river watersheds, the principal sources of fresh water for the Bay-Delta System. Mercury-enriched sediment now contaminates extensive downstream reaches of streams and rivers, adjoining floodplains, and the Bay-Delta Estuary. Concentrations of methylmercury in some resident fishes exceed 0.3 mg/kg (parts per million) wet weight, the U.S. Environmental Protection Agency's fish-tissue criterion for protecting the health of humans who consume noncommercial freshwater or estuarine fish.

A challenge to scientists and managers involved with restoration of this ecosystem is to avoid increasing exposure of biota to methylmercury, the highly toxic form that readily accumulates in exposed organisms and biomagnifies to high concentrations in fish and wildlife atop aquatic food webs. It would be desirable to eventually decrease methylmercury exposure in this ecosystem to levels where fishery resources, wildlife, and human health are unaffected; however, the development of an effective approach for achieving such a goal is presently hampered by our very limited knowledge of mercury cycling in this ecosystem. The production of methylmercury via the microbial methylation of inorganic divalent mercury in the environment is a key process affecting methylmercury concentrations in biota at all trophic levels. Natural processes and human activities – possibly including ecosystem restoration projects – that alter the net production of methylmercury (i.e., methylation minus demethylation) can influence the abundance of methylmercury in the ecosystem and the associated exposure of resident biota and humans who consume fish and other aquatic biota from the ecosystem.

The strategy provides guidance to the California Bay Delta Authority's Ecosystem Restoration Program, which is supporting ecological restoration of the mercury-contaminated Bay-Delta ecosystem. The overall goals outlined in the strategic plan for the Ecosystem Restoration Program for the Bay-Delta System are (1) to assist and recover at-risk native species, (2) to rehabilitate the Bay-Delta to support native aquatic and terrestrial biotic communities, (3) to maintain or enhance selected species for harvest, (4) to protect and restore functional habitat for both ecological and public values, (5) to prevent the establishment of additional non-native species, and (6) to improve or maintain water and sediment quality. Success in achieving most of these goals will hinge partly on the behavior and mitigation of mercury in the ecosystem, given that methylmercury contamination and exposure can adversely affect the health and reproductive success of native fish and wildlife, can diminish the benefits derived from fisheries, can degrade the quality of water and sediment, and can pose health risks to humans.

The goal of the mercury strategy is to provide a unifying framework for the integrated investigations needed to build a scientific foundation for ecosystem restoration, environmental planning, and the assessment and eventual reduction of mercury-related risks in the Bay-Delta ecosystem. The strategy was developed by a team of independent scientists, with input obtained in two public workshops attended by resource managers, environmental planners, scientists, and

other stakeholders from the region, as well as external technical experts. This document briefly describes the Bay-Delta ecosystem, summarizes current knowledge of mercury contamination and cycling in the ecosystem, considers the potential influences of ecosystem restoration activities on mercury cycling and methylmercury exposure, describes the development of the strategy, recommends six interactive core components of a mercury program focused on the ecosystem, and provides guidance for management of that program. The document does not recommend specific projects for funding, although useful mechanisms for selecting projects and project teams are discussed. In short, the mercury strategy provides a cohesive framework for ecosystem managers, partners, and participating scientists and offers guidance on certain, crucial aspects of an interdisciplinary mercury program.

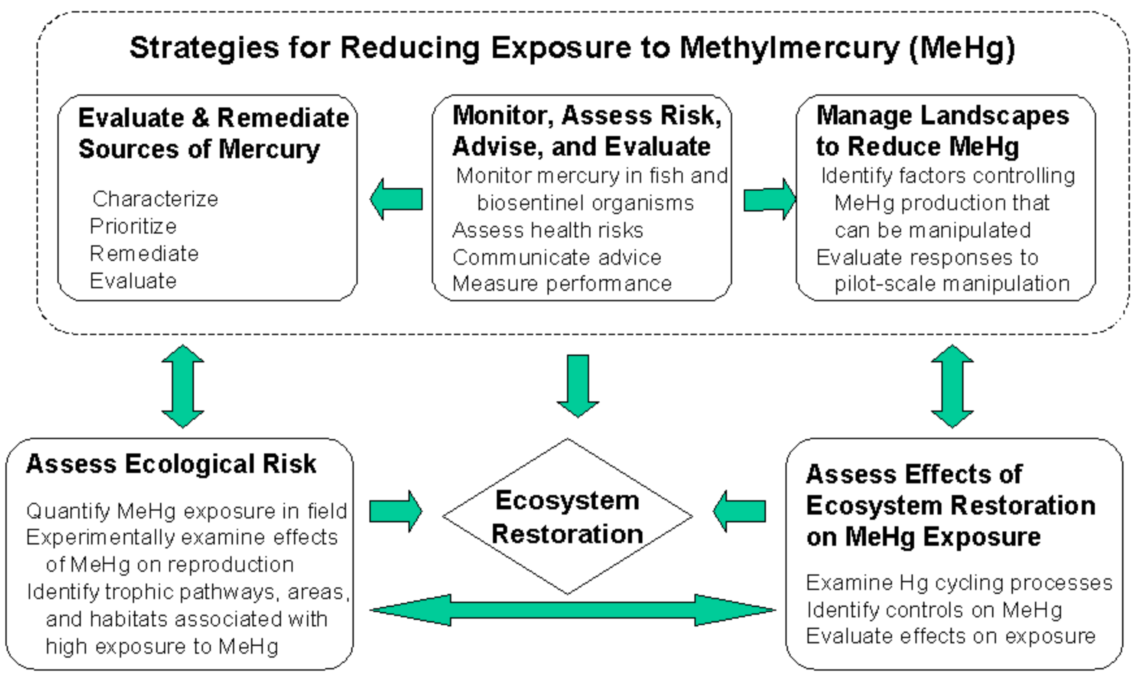
Clear definition of the problem or problems affecting ecosystem or human health is an essential first step in adaptive management, an operational process being used in the California Bay Delta Authority's Ecosystem Restoration Program in restoring the ecological health of the Bay-Delta ecosystem. In a toxicological sense, the primary problem with mercury in aquatic ecosystems can be defined as *biotic exposure to methylmercury*. It follows that an overall challenge for scientists and managers involved with ecological restoration and management in the Bay-Delta ecosystem is *to avoid increasing – and to eventually decrease – biotic exposure to methylmercury*. This challenge should provide a unifying sense of purpose for scientists, ecosystem managers, and other participants, as well as a unifying framework for adaptive management of this mercury-contaminated ecosystem.

The framework for the mercury strategy contains six core components. Each core component addresses one or more management goals and includes specific, supporting objectives pertaining to scientific activities (research and monitoring), management actions, or both. Management actions include source remediation, risk communication, ecosystem restoration, and landscape management. The six core components and their associated management goals are as follows.

Core Components	Management Goals
1. Quantification and evaluation of mercury and methylmercury sources	To identify mercury sources that contribute most strongly to the production and bioaccumulation of methylmercury
2. Remediation of mercury source areas	To identify remedial actions that can reduce loadings of mercury from sources to surface waters and decrease the exposure of aquatic biota to methylmercury
3. Quantification of effects of ecosystem restoration on methylmercury exposure	To document and understand the effects of ecosystem restoration in wetland, floodplain, and riverine habitats on the production and bioaccumulation of methylmercury in the Bay-Delta ecosystem
4. Monitoring of mercury in fish, health-risk assessment, and risk communication	To protect human health by assessing and reducing exposure to methylmercury-contaminated fish To provide a "performance measure" to gage methylmercury contamination of the Bay-Delta ecosystem during restoration

5.	Assessment of ecological risk	To protect fish and wildlife from adverse effects of methylmercury exposure
6.	Identification and testing of potential management approaches for reducing methylmercury contamination	To identify and evaluate potential landscape management approaches for reducing the production and abundance of methylmercury in the ecosystem, as well as the associated exposure of resident biota

The six core components are strongly interconnected. The interactions include linkages between scientific research and monitoring and linkages between scientific investigations and management actions. The linkages among the core components are illustrated below, where shaded arrows represent the flows of information and interactions needed to support decisions regarding both refinement of scientific investigations and adaptive management of mercury in the ecosystem. These linkages are utterly crucial for meeting the goals and objectives outlined for the strategy and for providing timely scientific input for adaptive management of mercury in the ecosystem. The evaluation of outcomes is also an important feature of the strategy.



This framework incorporates two approaches that have been applied for decades to reduce exposure to methylmercury: (i) reduction of mercury loadings and (ii) monitoring of mercury in fish as a scientific foundation for providing fish-consumption advice. A third, largely untested approach, management of contaminated landscapes to decrease the *in situ* net production of methylmercury, should be evaluated as a potential means of reducing methylmercury contamination and exposure in this ecosystem.

In evaluating effects of ecosystem restoration on mercury cycling, we recommend that the highest priority be given to examining effects of restoration on (1) the bioavailability of inorganic mercury for methylation and (2) the microbial production of methylmercury. Mercury contamination of aquatic environments is widespread in the Bay-Delta ecosystem. We believe that changes in bioavailability or methylation rates have much greater potential to significantly increase methylmercury exposure in this ecosystem than do changes in the spatial distribution of total (mostly inorganic) mercury. Studies in other aquatic ecosystems have shown that stimulation of methylation can increase the abundance of methylmercury and its uptake in biota by 10- to 20-fold, even in lightly contaminated environments where no mercury was added.

The influence of selenium on the abundance of methylmercury in food webs in the Bay-Delta ecosystem also merits investigation. Parts of this ecosystem, such as the San Joaquin River, are notably contaminated with selenium, which can inhibit the production of methylmercury and decrease its bioaccumulation in the food web. The linkage of selected mercury investigations to ongoing or planned studies of selenium biogeochemistry in the Bay-Delta system would be a cost-effective approach for examining interactions between selenium and mercury.

The competitive Proposal Solicitation Package process is an appropriate mechanism for allocating scientific effort to all but one core component (monitoring). An interdisciplinary effort will be needed to implement this strategy and to apply the resulting information towards adaptive management of the Bay-Delta ecosystem. Requests for proposals should, therefore, encourage development of interdisciplinary proposals by multidisciplinary teams of investigators. In addition to judging scientific merit and relevance to ecosystem management, the proposal review and selection process should critically assess the effectiveness of project teams, by considering team leadership, disciplinary composition, relevant experience, technical capabilities, and information transfer. Critical evaluation of the mercury problem in this ecosystem will be complicated by the spatiotemporal dynamics and complexity of the ecosystem, and project teams should contain the range of expertise needed to ensure defensible study design, analyses, and interpretation of data. It is recommended that, on average, about half of the team members on a project be "mercury specialists" and the remainder be scientists who bring other, essential expertise and knowledge on ecosystem processes, organismal biology, wetland ecology, sampling design, statistical analysis, risk assessment, modeling, or other pertinent applications. Project proposals should also demonstrate earnest commitments to provide timely information to ecosystem managers, to engage actively in facilitating the application of project results to adaptive management, and to participate substantively in the syntheses of results from multiple projects.

The establishment of a systematic monitoring program for mercury in fish is a high priority. The development and design of an effective monitoring program will require insightful leadership, input from managers and stakeholders, multidisciplinary technical guidance, and modest budgetary support. We recommend and have outlined a step-wise approach for development of a mercury-monitoring program, which would incorporate input from scientists, managers, and end-users of the monitoring data. Procedures for programmatic oversight of quality assurance should be in place at the onset of monitoring and other funded investigations to establish that the data emanating from multiple teams and laboratories are comparable and valid.

The transfer and sharing of information from mercury investigations should be actively facilitated, given the importance of rigorous interdisciplinary synthesis of results and timely provision of information for adaptive management. Effective mechanisms for rapid information transfer will be essential to ensure that interim data and information are available to facilitate timely information synthesis and application to management decisions. An annual meeting should be convened to provide a forum for sharing, discussion, integration, and review of interim results. Peer review by an external science panel should be a focal point of the meeting, providing constructive feedback at both the project and multi-project levels.

Effective coordination will be absolutely crucial to the success of this overall effort. It is strongly recommended that a full-time "mercury coordinator" be recruited or appointed to serve as a scientific leader, a facilitator, a communicator, and a point of contact on mercury issues for the Bay-Delta Program. The coordinator should have the leadership ability, scientific stature, and communication skills needed for effective synthesis and communication, and should have a key role in the organization and oversight of annual review meetings.

Mercury-polluted landscapes present an enormous challenge for ecosystem managers. An integrated mercury program would catalyze essential advances in understanding of the cycling, effects, and remediation of this toxic metal and should also enhance scientific understanding of the Bay-Delta ecosystem.

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I. INTRODUCTION

The mining of mercury and the use of mercury in gold mining have released large quantities of the metal to the environment of California since the mid 1800s (Alpers and Hunerlach 2000). Prolonged releases of mercury, including methylmercury, from historic mining sites can impact downstream environments for decades to centuries after mining operations cease (Lacerda and Salomons 1999, Ganguli et al. 2000, Rytuba 2000, Coolbaugh et al. 2002, Coulthard and Macklin 2003). In California and elsewhere, the transport of mercury-contaminated water and sediment from historic mercury- and gold-mining areas has contaminated aquatic environments and floodplains far downstream (Domagalski 1998, 2001, Ganguli et al. 2000, Rytuba 2000). These contaminated sites include the Sacramento and San Joaquin rivers, the Sacramento-San Joaquin Delta, and the San Francisco Bay. The Sacramento River watershed, the primary source of fresh water for the Bay-Delta, was a site of intensive historic mining for gold and mercury and is an important modern source of mercury and methylmercury for the Bay-Delta (Domagalski 2001, Choe and Gill 2003, Choe et al. 2003).

Concerns about mercury pollution stem largely from the potential adverse effects of dietary exposure to methylmercury, a highly toxic form that readily accumulates in biota and can biomagnify to harmful concentrations in organisms atop aquatic food webs (Mahaffey 2000, Clarkson 2002, Wiener et al. 2003). Documented consequences of methylmercury pollution include (1) direct adverse effects on the health and fitness of fish, wildlife, and humans, (2) contamination of fishery resources that diminishes their nutritional, cultural, socioeconomic, and recreational benefits, and (3) socio-cultural damage to indigenous peoples who had fished for subsistence (Mahaffey 2000, NRC Committee on Toxicological Effects of Methylmercury 2000, Wheatley and Wheatley 2000, Clarkson 2002, Wiener et al. 2003). Nearly all of the mercury in fish is methylmercury (Grieb et al. 1990, Bloom 1992), and consumption of fish is the primary modern pathway of methylmercury exposure in humans (NRC Committee on the Toxicological Effects of Methylmercury 2000, Mahaffey 2000, Clarkson 2002, Schober et al. 2003). Dietary exposure to methylmercury can be substantial for predatory fish and wildlife atop aquatic food webs (Wiener et al. 2003), and recent studies suggest that the reproductive success of some nesting aquatic birds is being adversely affected by methylmercury exposure in the Bay-Delta ecosystem (Hoffman et al. 1998, Heinz 2003, Schwarzbach and Adelsbach 2003).

The historic contamination and continuing transport and loading of mercury to the Bay-Delta ecosystem have significant implications for its ecological restoration and management. Concentrations of methylmercury in food webs supporting production of fish and aquatic wildlife are strongly correlated with the supply of methylmercury (Hecky et al. 1991, Kelly et al. 1997, Gilmour et al. 1998, Paterson et al. 1998, Heyes et al. 2000, Wiener et al. 2003). Hence, the production of methylmercury in aquatic ecosystems via the microbial methylation of inorganic mercury (reviewed in Benoit et al. 2003) is a key process affecting methylmercury concentrations in aquatic invertebrates, fish, and wildlife (reviewed in Wiener et al. 2003). It follows that the array of natural processes, human activities, and disturbances affecting the rates of production and degradation of methylmercury on the landscape can markedly influence the methylmercury content of aquatic biota and the associated exposure of consumers of these biotic resources.

Wetlands, which are generally considered important sites of microbial methylation on the landscape, can be important sources of methylmercury for downstream waters (Hurley et al. 1995, St. Louis et al. 1996, Waldron et al. 2000, Domagalski 2001, Sellers et al. 2001). The restoration of wetlands, particularly in areas where the abundance of mercury in soils or sediments has been elevated by mining or other human activities, could accelerate the production of methylmercury and increase the contamination of aquatic biota (Naimo et al. 2000, Wiener and Shields 2000). In addition, flooding of vegetated wetlands or uplands or fluctuating water levels during tidal cycles could stimulate microbial methylation of inorganic mercury, increasing concentrations of methylmercury in water and biota (Hecky et al. 1991, Hall et al. 1998, Paterson et al. 1998, Bodaly and Fudge 1999, Hall et al. *in press*).

This report presents a strategy for addressing key questions concerning the biogeochemical cycling and potential effects of mercury in the Bay-Delta ecosystem. The *goal* of the mercury strategy is to provide a holistic framework for integrated investigations needed to build a scientific foundation for ecosystem restoration, environmental planning, and the assessment and eventual reduction of mercury-related risks in the Bay Delta ecosystem.

II. THE SAN FRANCISCO BAY-DELTA ECOSYSTEM

The Ecosystem

The modern San Francisco Bay-Delta ecosystem can be described as three physiographic areas: the San Francisco Bay and its estuarine embayments, the Sacramento-San Joaquin River Delta, and the Sacramento and San Joaquin River watersheds that drain into the Delta. Conditions across this ecosystem range from the marine environment of central San Francisco Bay to high-gradient streams fed largely by snow melt in the Sierra Nevada. The "Delta", once an expansive area of tidal and non-tidal wetlands, lies at the convergence of the Sacramento and San Joaquin rivers (Figure 1).

The Sacramento and San Joaquin rivers together drain about 37 percent of California. The Sacramento River basin is the state's largest (nearly 70,000 square kilometers), with annual runoff of about 27-billion cubic meters, about one-third of the total runoff in California and about 5 to 6 times that of the San Joaquin River basin (http://waterdata.usgs.gov/nwis/). The Sacramento River is a major source of drinking water for the state, as well as the principal source of irrigation water for agriculture in the Sacramento and San Joaquin valleys (Central Valley). The Sacramento River basin includes all or parts of five physiographic provinces: the Sacramento Valley, the Sierra Nevada, the Coast Ranges, the Cascade Range, the Klamath Mountains, and the Modoc Plateau. The northernmost area (Modoc Plateau) is a high desert plateau with cold snowy winters, moderate rainfall (about 30 cm), and hot dry summers. Other high-elevation portions of the basin (including the Cascade, Coast, and Sierra Nevada ranges) receive more precipitation (up to 200-300 cm per year) with melting winter snow yielding most of the spring and summer runoff.

The San Joaquin River basin, which drains the Central Valley from the south, is bounded by the Sierra Nevada to the east, the Coast Ranges to the west, and the Tehachapi Mountains to the south. The San Joaquin River basin is more arid than the Sacramento River basin, with hotter summers and milder winters. The San Joaquin River receives water from tributaries draining the Sierra Nevada and Coast Ranges, and except for streams discharging directly to the Sacramento-San Joaquin Delta, is the only surface-water outlet from this basin.

Figure 1. Map of the San Francisco Bay-Delta, which includes the San Francisco Bay and the delta of the Sacramento and San Joaquin rivers (source: California Bay Delta Authority, Bay-Delta Program).

The modern San Francisco Bay can be characterized as an ecologically young, but extensively modified, estuarine ecosystem. The estuary was formed 15,000 to 18,000 years ago, when rising sea waters from glacial melting entered the Golden Gate, inundating what are now the major embayments of the San Francisco Bay (San Pablo Bay, Carquinez Strait, Suisun Bay, Grizzly Bay, Honker Bay), transforming a riverine system into an extensive and complex estuary (Atwater 1979). Together, the Sacramento-San Joaquin Delta and the embayments of San Francisco Bay form the largest estuary on the West Coast of the United States, with a combined area of about 3,000 square kilometers. The Delta is estuarine through its lower end, but is almost completely influenced by tidal cycles. About 72 percent of the Delta land area is in agricultural production, which was engineered via a complex system of dikes, drainage ditches, irrigation diversions, pumps, and floodgates. This complex drainage pattern, combined with a strong tidal currents, create large tidal excursions where distinct water parcels, with distinct chemical characteristics, can travel many miles on a given ebb or flood tide in patterns that are difficult to predict or anticipate. Freshwater inflows (excluding precipitation) to the Delta are mainly from the Sacramento River (about 75-80 percent), with most of this inflow during January to April.

Mining and Mercury

The mountain ranges that surround California's Central Valley and drain into the Sacramento and San Joaquin watersheds contain extensive mineral deposits. Discovery of gold deposits in the Klamath Mountains and Sierra Nevada stimulated the California Gold Rush in 1848, and an abundance of mercury from hundreds of mercury mines in the Coast Ranges facilitated the rapid historic proliferation of gold-mining operations (Figure 2) that used the mercury-amalgamation process to extract gold (Gilbert 1917, Alpers and Hunerlach 2000). Hundreds of hydraulic gold-placer mines operated on the east side of the Central Valley, where tens of millions of cubic meters of auriferous gravels and overlying soils were excavated annually by hydraulic mining. The resulting mining debris choked streams and rivers downstream of mining sites, and in some cases valleys were nearly filled with debris. About 100,000 metric tons of mercury were produced by mercury-mining operations in the Coast Ranges, and about 12,000 metric tons of this were used in gold mining in California, with annual losses at mine sites ranging from about 10 to 30 percent of the mercury used (Alpers and Hunerlach 2000). The effects of these gold- and mercury-mining activities are evident in the Bay-Delta Estuary far downstream (Conomos et al. 1985). Consequently, mercury from a mineral belt associated with Cenozoic hydrothermal deposits in the Coast Ranges (Rytuba 1996) now contaminates environments extending from San Francisco Bay (Hornberger et al. 1999) to the Coast Ranges, the Sierra Nevada, and far beyond (Schuster et al. 2002).

During 1900-1960, several billion cubic meters of alluvial material was dredged for gold, and millions of pounds of mercury were discharged to the environment in association with these operations. These alluvial "dredge fields" are generally downstream from dams on the major tributaries – including the Feather, Yuba, American, and Merced rivers – and are situated in floodplains that provide critical habitat to anadromous fishes. Many of the dredge fields contain mercury-contaminated tailings from hydraulic-mining activities that took place further upstream, before dams were constructed. Additional mercury was released to the environment in association with dredging processes at these alluvial sites.

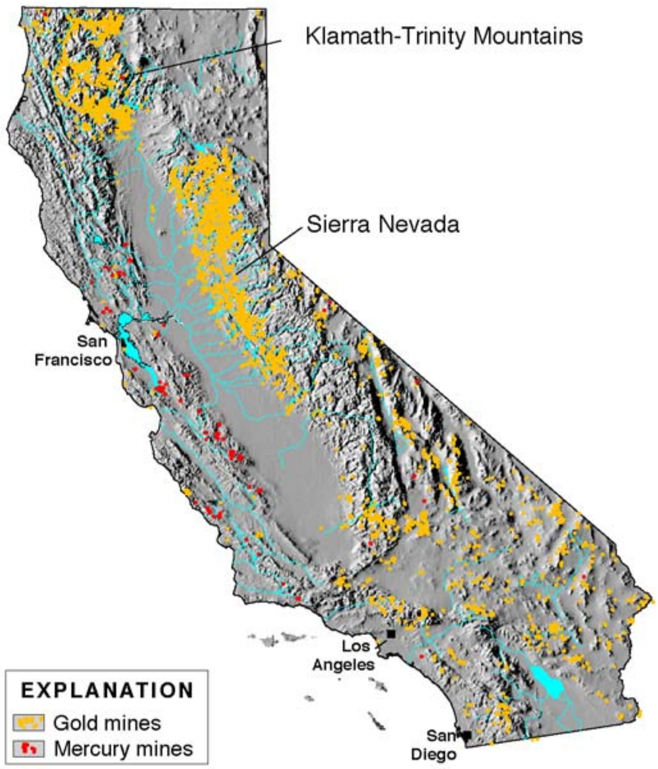

Figure 2. Locations of known mercury mines and gold mines in California (source: U.S. Geological Survey, Sacramento, California)

The accumulation of contaminated debris from gold mining caused a notable loss of depth in parts of the San Francisco Bay (Nichols et al. 1986, Cappiella et al. 1999). In the past 50 years, however, the amount of additional sedimentation attributable to the Gold Rush has declined substantially, and further declines are predicted (Jaffe et al. 1998*a*). All of the major rivers in the Sacramento River basin (Sacramento, Feather, American, Yuba) are impounded. The impoundments have decreased sediment export from the basin (Goals Project 1999), and the suspended sediment load of the Sacramento River has declined since 1960 (Krone 1996). Given that about 90 percent of the total mercury load to the Bay-Delta ecosystem from the Sacramento River is sediment borne (Foe 2002), it can be reasonably inferred that mercury loads have correspondingly declined and that future activities affecting sediment budgets could substantially affect mercury loadings. Recent work by the U.S. Geological Survey indicates that large areas of the estuary have been eroding during recent decades (Jaffe et al. 1998*a*, 1998*b*, Cappiella et al. 1999).

Mercury Cycling

The mercury problem in the Bay-Delta Estuary is extremely complex and somewhat unusual. Most industrial point sources of mercury in North America have been curtailed, and much of the scientific attention now focuses on contamination associated with atmospheric emissions and deposition. The Bay-Delta ecosystem, in contrast, receives substantial mercury from former mine sites and historically contaminated waterways. Mercury concentrations in 75-cm striped bass (*Morone saxatilis*) from the Bay and Delta range from 0.3 mg/kg to greater than 1.5 mg/kg wet weight (California State Department of Public Health 1971, Fairey et al. 1997, Davis et al. 2002). In comparison, striped bass of the same size from the Chesapeake Bay, the largest estuary on the East Coast of the United States, range from 0.1 to 0.5 mg/kg wet weight (Gilmour and Riedel 2000). Atmospheric deposition is the primary modern source of mercury to the Chesapeake Bay watershed (Mason et al. 1997*a*, 1997*b*).

Understanding of mercury cycling in the Bay-Delta ecosystem has advanced markedly in the last 3 years, as findings of recent investigations have become available. Figure 3 is a conceptual model of mercury transport and cycling in the San Francisco Bay-Delta ecosystem, derived from a synthesis of recent investigations. Historically, mine sites in the Sierra and Coast ranges have been the major anthropogenic sources of mercury to the Bay-Delta ecosystem, and these loadings would have been mostly sediment-borne. Analyses of recent samples from former mercury-mining sites and thermal springs have provided information on the magnitude and speciation of mercury exported from the sites (Ganguli et al. 2000, Rytuba 2000, Churchill and Clinkenbeard 2003). Some of the mine sites in the Cache Creek watershed, an important source of mercury in the Sacramento River basin (Domagalski 2001), have been characterized recently (Churchill and Clinkenbeard 2003, Suchanek et al. 2003), including assessments of erosional and aqueous loads of mercury downstream. Mercury is transported via erosion from Cache Creek mine sites primarily during the rainy season (Churchill and Clinkenbeard 2003), although more sampling is needed during storm events to quantify associated loads.

The forms of mercury eroding from mining sites in the Coast Range are mainly cinnabar and metacinnabar (Bloom 2003). These forms have low solubility under oxic conditions but can dissolve and become available for methylation in anoxic, sulfidic sediments (Benoit et al. 2001, Bloom 2003). Organic matter can also solubilize cinnabar (Ravichandran et al. 1998, Haitzer et al. 2002), although the effect of this dissolution on methylation has not been determined. Thermal springs in the Cache Creek watershed can be a significant source of mercury on the landscape at the sub-watershed scale, particularly in dry years when there is little runoff from abandoned mine sites (Domagalski et al. 2003). Thermal springs are also substantial sources of sulfate, which can stimulate the methylation of inorganic, divalent mercury by increasing the activity of mercury-methylating, sulfate-reducing bacteria (Rytuba 2000, Benoit et al. 2003).

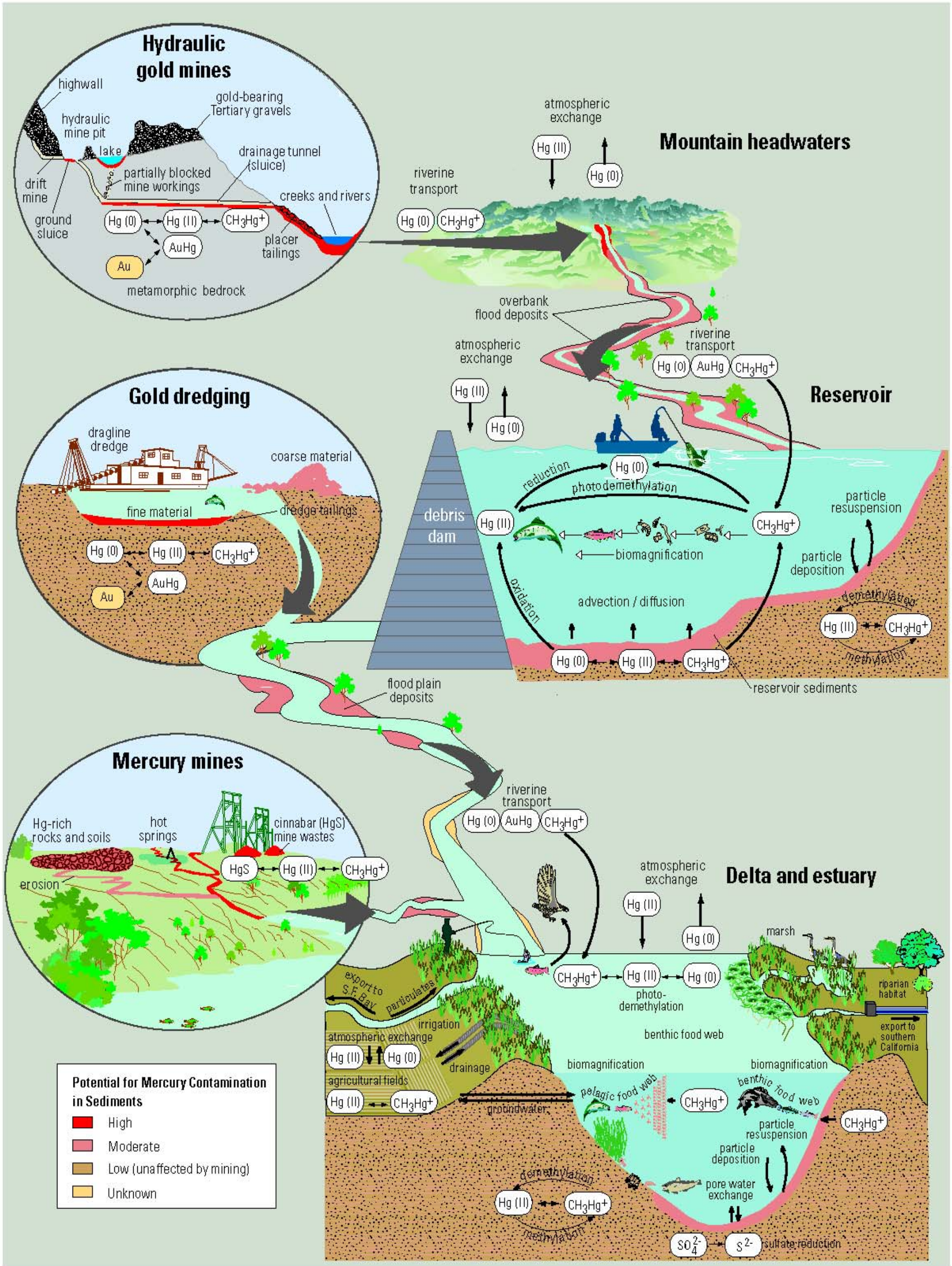

Figure 3. Conceptual model of mercury sources and cycling in the San Francisco Bay-Delta ecosystem, which is here defined as the combined watershed, Delta, and Bay. The figure was modified from Alpers and Hunerlach (2000) and Stephenson et al. (2002), with further input based on recent unpublished work by Charles Alpers (U.S. Geological Survey, Sacramento, California), Mark Stephenson (California Department of Fish and Game, Moss Landing, California), and their colleagues.

The release of mercury from gold mines in the Sierra, and the form of mercury in those mines has been less well studied (relative to mercury mines), although initial observations indicate that it may be more readily methylated (Heim et al. 2003, Gill et al. 2002, Slotton et al. 2002*a*). Elemental mercury and gold-mercury amalgam are often visible in streams draining hydraulically mined areas of the Sierra Nevada and in the dredged goldfields downstream, such as those on the Yuba and American rivers (Michael Hunerlach, U.S. Geological Survey, Sacramento, California, unpublished data; Rick Humphreys, State Water Resources Control Board, Sacramento, California, unpublished data). Information on the speciation, mobility, and bioavailability (for methylation) of mercury from gold mining would be useful for developing strategies for remediation (Kim et al. 2003). The U.S. Geological Survey is investigating mercury contamination and bioaccumulation in the Sierra Nevada, and initial data from these studies are becoming available (Alpers et al. 2001, 2002*a*, 2003). Data concerning mercury and methylmercury in water, sediment, and biota from sites in the Bear River watershed are available online (http://ca.water.usgs.gov/mercury/bear-yuba/).

Spatial and temporal patterns in concentrations of total mercury and methylmercury in water and biota were recently characterized for the Cache Creek watershed (Domagalski 2001, Domagalski et al. 2003, Slotton et al. 2002*b*, Suchanek et al. 2003), yielding useful data for assessing the efficacy of future restoration efforts there. However, baseline information on concentrations of mercury and methylmercury in stream-bank and bed sediments downstream from the mine sites is comparatively sparse. Yet spatial patterns in the concentrations and speciation of mercury in mine drainage, stream-water, and sediment below mine sites clearly shows that methylmercury is being produced in such zones (Ganguli et al. 2000, Rytuba 2000, Bloom 2003).

Quantification of the relative importance of mercury sources to the Bay-Delta Estuary has only recently been attempted. Analyses of sediment cores show that mercury-contaminated sediments were being deposited in San Pablo Bay (northern San Francisco Bay) between 1850 and 1880, probably from incoming debris from hydraulic gold mining (Hornberger et al. 1999). Moreover, maximum concentrations in the cores were 20 times the concentrations in sediments deposited before 1850. Domagalski (2001) identified the Cache Creek watershed and unknown sources in the upper Sacramento River basin as the major source regions for mercury to the Bay-Delta Estuary. An initial budget for total mercury constructed by Foe (2002) shows that both the Sacramento and San Joaquin rivers, as well as eroding contaminated sediments in Suisun Bay, are present sources of mercury to the Bay-Delta.

Historically contaminated sediments are sources of residual mercury from historic mining operations. The present distribution of contaminated sediments extends from small streams below mine sites, to extensive alluvial areas in floodplains where gold was dredged, down gradient through the Delta and San Francisco Bay. The modern distribution of contaminated sediments has been partially described. Recent surveys, for example, have provided significant new information on the abundances of mercury and methylmercury in sediments in the Delta (Cappiella et al. 1999, Heim et al. 2003, Slotton et al. 2002*a*). Gill et al. (2002), who estimated fluxes from Delta sediments, found that sediment-water exchange of total mercury and methylmercury rivaled external riverine sources during low-flow conditions, whereas external sources dominated during high flow. There were large temporal and spatial variations in estimated sediment-water exchanges of total mercury and methylmercury in the Delta in Gill's study. Mercury movement via bed load and sediment transport is difficult to quantify, but merits attention. Rigorous assessments of the contribution of contaminated sediments to overall budgets for mercury and methylmercury, with emphasis on active biogeochemical pools that contribute methylmercury to the benthic and pelagic food webs, are urgently needed.

Inputs of mercury via atmospheric deposition are small relative to land-based sources in the Bay-Delta ecosystem. In the Cache Creek watershed, mercury loading from mines sites far exceeds atmospheric deposition (Churchill and Clinkenbeard 2003), assuming that local emission and re-deposition is not large, an assumption that has not been tested. Moreover, the input of mercury from atmospheric deposition to the entire watershed appears to be less than the loadings from the Sacramento and San Joaquin rivers. Very little of the mercury entering a terrestrial catchment in atmospheric deposition is exported in surface water; most is retained within the basin (Hurley et al. 1995, Mason et al. 1997*a*, Lorey and Driscoll 1999), suggesting that non-atmospheric sources should dominate mercury loading to aquatic environments in this ecosystem. Mercury deposition rates have been measured for only a small part of the watershed (Tsai and Hoenicke 2001), however, and retention factors for mercury deposited in the watershed are unknown. Steding and Flegal (2002) provided preliminary evidence of long-range transport of mercury across the North Pacific to coastal California. Concentrations of mercury in coastal rainwater were greatest in storms associated with air masses that received industrial emissions from the Asian continent. In addition, concentrations in rain at an urban site in the San Francisco metropolitan area were elevated relative to those at a coastal site near Santa Cruz, possibly due to urban emissions of mercury (Steding and Flegal 2002).

The availability of inorganic mercury for methylation can vary greatly (Benoit et al. 1999*a*, 2001, Bloom 2003), and newly deposited mercury may be much more reactive than mercury that has been residing in the ecosystem (Hintelmann et al. 2002). The relative bioavailability of mercury derived from atmospheric deposition vs. residual mercury from mining sources is an important information gap – one that hinders the confirmation of mercury sources contributing to internal production of methylmercury in this ecosystem.

The internal cycling of mercury and methylmercury within the ecosystem is only beginning to be understood. The dominant loss terms for mercury in the Bay-Delta ecosystem, based on the present state of knowledge, are loss to agricultural fields, export to the ocean, export to southern California, evasion to the atmosphere, and sedimentation and burial (Figure 3); the relative magnitude of these fluxes is poorly understood. In areas of the estuary where sediments from hydraulic mining are now being eroded (Jaffe et al. 1998*b*, Cappiella et al. 1999), sedimentation and burial of mercury are presumably nil. Across the estuarine salinity gradient, there are apparent sources of total mercury and sinks of methylmercury within the estuary (Foe 2002, Choe and Gill 2003, Choe et al. 2003). Particulate total mercury is the dominant phase in waters of the estuary, and much of the filter-passing total mercury is associated with colloids (Choe et al. 2003). Roughly half of the waterborne methylmercury in the estuary is associated with particles, and much of the filter-passing methylmercury is colloidal (Choe and Gill 2003). Waterborne total mercury and methylmercury seem to be strongly associated with organic matter in the estuary (Choe and Gill 2003, Choe et al. 2003).

Methylmercury is produced primarily by sulfate-reducing bacteria (Compeau and Bartha 1985, Gilmour et al. 1992, Pak and Bartha 1998, King et al. 2001), and the most important sites of microbial methylation in the Bay-Delta ecosystem are expected to be oxic-anoxic interfaces in sediments, wetlands, and seasonally inundated, vegetated habitats (St. Louis et al. 1994, Hurley et al. 1995, Kelly et al. 1997, Gilmour et al. 1998). Within the Delta, marshes seem to be more significant sites of methylmercury production than open-water sediments. Marshes, which have higher concentrations of methylmercury and higher methylation potential than do sediments in open-water areas (Heim et al. 2003, Slotton et al. 2002*a*), can export methylmercury via tidal currents (Gill et al. 2002). Methylmercury can be transported from the site of methylation by several processes, including resuspension of bed sediments, diffusive and advective (e.g., tidal) solute fluxes, hydrologic transport with sediment or colloids, and uptake into mobile aquatic biota. Methylmercury can be lost by the processes of microbial and photo demethylation, burial in deposited sediment, and emigration or harvest of contaminated biota. Benoit et al. (2003) have reviewed current understanding of methylation and demethylation processes.

The distribution of methylmercury in open-water sediments in the Delta has been recently studied (Heim et al. 2003, Gill et al. 2002, Slotton et al. 2002*a*). There is less information for marshes, diked islands, agricultural lands, and seasonally flooded areas, and budgets for the major sources and sinks of methylmercury within the Delta and the ecosystem remain poorly constrained. The relative rates of net methylmercury production across the complex mosaic of habitats in the Bay-Delta ecosystem are not well known. Methylmercury is being produced and bioaccumulated to high concentrations in streams near mercury mines, where methylation probably occurs in mine wastes (calcines) and stream sediment (Rytuba 2000, Ganguli et al. 2000, Slotton et al. 2002*b*). Methylmercury is also being formed and bioaccumulated in aquatic habitats affected by abandoned placer-gold mines in the Sierra Nevada (Alpers et al. 2002*a* and USGS data on-line at http://ca.water.usgs.gov/mercury/bear-yuba/). Spatial variation in methylation in Delta marshes and submerged sediments appears to be substantial (Gill et al. 2002, Slotton et al. 2002*a*). Seasonal variation in methylmercury accumulation in sediments is also apparent, with maxima mainly during the warmest temperatures, as noted in other ecosystems (Ramlal et al. 1993). Sediments appear to be a net source of methylmercury to the water column (Gill et al. 2002). Stephenson et al. (2002), who employed a mass balance approach, suggest that the central Delta is a sink for methylmercury, due to photodemethylation or storage via bioaccumulation. Slotton et al. (2002*a*) suggest that inorganic mercury newly delivered from upstream sources is more readily methylated and bioaccumulated than inorganic mercury stored in the central Delta.

The rates of methylation in this ecosystem will be influenced by the bioavailability of inorganic mercury to methylating bacteria, the concentration and form of inorganic mercury, and the distribution and activity of methylating bacteria. Studies to date suggest that the bioavailability of inorganic mercury in the Bay-Delta ecosystem varies with the source and that the rate of methylation varies in time and space. There is a significant relation between the abundances of total mercury and methylmercury across ecosystems, but the concentration of inorganic mercury accounts for little of the variation in methylmercury production when data for multiple ecosystems are combined (Benoit et al. 2003).

Continuing work on mercury in the Bay-Delta ecosystem should link process-based studies to descriptive (mensurative) studies, monitoring, restoration activities, and model development. Ambient concentrations of methylmercury provide an integrative measure of the impact of all the processes influencing the abundance of methylmercury, such as loading, flux, methylation, and demethylation. A quantitative model of methylmercury production across habitats in the Bay-Delta ecosystem would be useful for planning restoration strategies, and development of such a model should be a long-term goal of research. The next phase of mercury investigations in the Bay-Delta ecosystem should seek to understand the relative rates of methylmercury production across habitat types and salinity gradients, as well as the processes that contribute to differences in the abundance of methylmercury among habitats and its bioaccumulation in food webs. The descriptive phase of mercury studies in the Bay-Delta ecosystem is not yet complete, and the estimation of mass-balance fluxes of methylmercury (and to a lesser extent, total mercury) remains a particularly important objective. The scientific effort on mercury in the Bay-Delta ecosystem, however, should soon undergo a transition from the descriptive to a more mechanistic phase. Such a transition is appropriate given that an understanding of controlling processes will be needed to develop predictive models useful for guiding ecosystem restoration and management.

The processes of bioaccumulation and biomagnification strongly influence concentrations of methylmercury in fish, birds, and mammals atop aquatic food webs (Wiener et al. 2003). Methylmercury readily crosses biological membranes and accumulates to concentrations in aquatic organisms that vastly exceed concentrations in ambient surface waters; for example, concentrations in fish commonly exceed those in the water in which they reside by a factor of 10^6 to 10^7. Nearly all of the mercury accumulated in fish is methylmercury, obtained almost entirely via dietary uptake. Concentrations of methylmercury in fish increase with increasing age or size, because of the very slow rate of elimination relative to the rate of uptake.

Biomagnification of methylmercury in aquatic food webs has been widely documented, and patterns of biomagnification are similar even in aquatic systems that differ markedly in ecosystem characteristics, mercury source, and intensity of pollution (Wiener et al. 2003). Inorganic mercury, in contrast to methylmercury, is not readily transferred through successive trophic levels and does not biomagnify in food webs. The concentration of methylmercury increases up the food web from water and lower trophic levels to fish and piscivores, and the fraction of mercury present as methylmercury also increases with increasing trophic level through fish. The fraction of mercury present as methylmercury can vary greatly in organisms, such as aquatic invertebrates, in trophic levels below fish. The abundance of methylmercury in the lower trophic levels is strongly correlated with the supply of methylmercury. In fish within a given trophic level, spatial variation in mercury levels is also strongly influenced by variation in the net production of methylmercury and its entry into the base of the food web. Concentrations of methylmercury in fish increase with increasing trophic position, and variation in trophic position accounts for much of the local variation in mercury concentration, both within and among species within a given water body. Thus, ecological factors, such as feeding relations and food-chain length, can strongly affect methylmercury exposure in biota atop aquatic food webs.

Concentrations of methylmercury (quantified as total mercury) in several species of fish recently sampled from the Bay-Delta and tributary streams exceed 0.3 mg/kg (parts per million) wet weight (Slotton et al. 2002*a*, 2002*b*, Davis et al. 2003), a fish-tissue criterion established by the U.S. Environmental Protection Agency for the protection of humans who eat noncommercial fish. Within a given species of fish or aquatic macroinvertebrate, there is substantial spatial variation in concentrations of methylmercury in this ecosystem (Slotton et al. 2002*a*, 2002*b*, Davis et al. 2003), reflecting the influence of mercury sources, methylating environments, and other, unidentified causal processes or factors.

Ecological Status of the Bay-Delta

In the last 150 years, the Bay-Delta Estuary has been modified greatly by human activities, including the diking and filling of wetlands, the reduction of freshwater inflow by more than half, the introductions of exotic species, and substantial anthropogenic inputs of nutrients, sediments, and potentially toxic contaminants (Nichols et al. 1986, van Geen and Luoma 1999). The area of tidal wetlands, for example, declined 95 percent, from 2200 square kilometers before 1850 to about 125 square kilometers in 1986 (Nichols et al. 1986).

The estuary is a spatially variable and temporally dynamic ecosystem, exhibiting biological change and pronounced variation in ecological structure and function on time scales ranging from diurnal to decadal (Cloern 1996, Jassby et al. 2002). Primary production in the Delta, which is rarely nutrient limited, is highest in the spring, much lower in summer, and lowest in winter and autumn (Jassby et al. 2002). During 1975-1995, primary production in the Delta declined 43 percent and varied as much as 3-fold between successive years (Jassby et al. 2002). The abundances of several species of native resident fish and zooplankton have decreased in recent decades, while the abundances of exotic invaders have increased (Nichols et al. 1986, Carlton et al. 1990, Bennett and Moyle 1996, Kimmerer and Orsi 1996, Orsi and Mecum 1996, Matern et al. 2002). The declines in native fish and zooplankton may be caused partly by the decrease in primary production, given that particulate organic matter from internal phytoplankton production is the dominant food supply for the Delta's planktonic food web (Sobczak et al. 2002).

Trophic pathways in the estuary have been strongly influenced by exotic species, particularly the Asian clam *Potamocorbula amurensis*, which has contributed to decreased primary production and food limitation (Kimmerer and Orsi 1996, Orsi and Mecum 1996, Jassby et al. 2002). This euryhaline bivalve invaded the Bay in 1986 and in 2 years had spread throughout the estuary (Carlton et al. 1990, Nichols et al. 1990). The clam feeds on phytoplankton (Canuel et al. 1995) and has altered trophic pathways in the estuary by diverting much of the primary production from the pelagic to the benthic food web (Alpine and Cloern 1992).

The effects of the observed dynamics in primary production and trophic pathways on the food-web transfer and compartmentalization of methylmercury in this ecosystem are not known. Given that biota in upper trophic levels obtain methylmercury almost entirely from dietary uptake, an understanding of their exposure to and bioaccumulation of this toxic metal will hinge in part on a knowledge of trophic pathways and ecological processes supporting their production.

III. The California Bay Delta Authority's Ecosystem Restoration Program

The mission of the Bay-Delta Program is to develop and implement a long-term, comprehensive plan for restoring the ecological health and improving water management for beneficial uses of the Bay-Delta ecosystem (Jacobs et al. 2003). The Ecosystem Restoration Program is the principal California Bay Delta Authority program involved with restoring the ecological health of the Bay-Delta ecosystem. The restoration goals in the Ecosystem Restoration Program's strategic plan are (1) to assist and recover at-risk native species, (2) to rehabilitate the Bay-Delta to support native aquatic and terrestrial biotic communities, (3) to maintain or enhance selected species for harvest, (4) to protect and restore functional habitat for both ecological and public values, (5) to prevent the establishment of additional non-native species, and (6) to improve or maintain water and sediment quality (CALFED Bay-Delta Program 2000*a*). The Ecosystem Restoration Program applies an adaptive management approach to restoration, along with rigorous external review.

Success in achieving most of the Ecosystem Restoration Program's strategic goals will depend in part on the behavior and mitigation of mercury in the ecosystem. For example, the reproductive success of some native birds may be adversely affected by methylmercury exposure in parts of the ecosystem (Schwarzbach and Adelsbach 2003, Heinz 2003), and mercury contamination of fish (May et al. 2000, Thompson et al. 2000, Davis et al. 2002) can diminish some of the benefits derived from recreational fisheries. The reproductive success of fish can be greatly reduced by methylmercury exposure (Latif et al. 2001, Hammerschmidt et al. 2002, Wiener et al. 2003, Drevnick and Sandheinrich 2003), but reproductive effects of methylmercury on fish inhabiting the Bay-Delta ecosystem have not yet been examined. The quality of sediment and water in an ecosystem are clearly degraded if methylmercury is being bioaccumulated to levels that harm or otherwise devalue fish, shellfish, and wildlife.

A number of planned remedial and restoration activities in the Bay-Delta ecosystem may alter the production and bioaccumulation of methylmercury. Remedial actions at mercury source areas, such as mine sites, could reduce mercury loadings and methylmercury exposure. There is strong evidence that the export of mercury from historic mercury- and gold-mining sites causes significant contamination of biota downstream (May et al. 2000, Slotton et al. 2002*b*). Mercury loads from a number of mine sites have been estimated, and erosion control has been identified as the best restoration method for mercury in the solid phase (Churchill and Clinkenbeard 2003).

The selective remediation of contaminated bed sediments and stream banks may also reduce mercury loadings. The contribution of the mercury-contaminated sediments that are distributed throughout much of the Bay-Delta ecosystem to the methylmercury accumulated by biota is poorly understood. Mitigation activities at some contaminated sites may be useful, but more information on the contribution of contaminated streambeds and overbank sediments to the production and bioaccumulation of methylmercury, as well as current mercury loadings, would be desirable.

The effects of certain ecosystem restoration activities on the net production and bioaccumulation of methylmercury should be evaluated. Restoration could alter a variety of environmental variables that influence mercury cycling, methylation, demethylation, and bioaccumulation. Such variables include mercury loadings, habitat type, hydroperiod, oxic-anoxic boundaries in water and sediment, microbial activity, temperature, water chemistry, trophic status, and food-web structure. The relative influence of many of these factors on the production and bioaccumulation of methylmercury remains poorly quantified (for recent reviews, see Benoit et al. 2003, Wiener et al. 2003). The general types of restoration activities considered most likely to affect mercury cycling and methylmercury exposure include wetland restoration, restoration of seasonal floodplains, channel reconstruction, and dam removal.

A number of restoration projects have proposed to use tailings (dredged gravels) from the gold dredge fields as a source of gravel for injection to streams to enhance spawning habitat, for reconstructing channels, or for other aspects of restoration. The fine grain-size fraction in these dredge tailings can be quite elevated in total mercury concentration (Ashley et al. 2002). Recent data show that the bioaccumulation of mercury can be significant in ponds and wetlands associated with dredging environments, indicating that some of the mercury lost to these tailings through the gold-recovery process is available for microbial methylation and subsequent uptake by biota (Charles N. Alpers, U.S. Geological Survey, Sacramento, California, personal communication). The consequences of ongoing and proposed aquatic restoration projects involving the use of dredge tailings should be assessed, given the potential significance of dredged areas as sources of mercury and methylmercury in the ecosystem.

Further examples of potential linkages between restoration activities and mercury cycling are illustrated below.

Wetland restoration and inundation of floodplains: Potential changes in the extent of methylmercury-producing habitat and in food-web structure. Wetland habitats are known to support high rates of microbial methylation (St. Louis et al. 1994, Gilmour et al. 1998, King et al. 1999), and initial data show that some Delta marshes produce and export methylmercury (Gill et al. 2002, Slotton et al. 2002*a*). However, wetland and floodplain habitat varies greatly across the salinity gradient in the estuary, and little is known about the relative rates of methylmercury production and export across these habitat types. Shallow sediments and flooded soils are also potentially important sites of methylmercury production (Hall et al. *in press*). Habitat changes resulting from wetland restoration and seasonal floodplain inundation could also influence food-web structure, affecting exposure to and bioaccumulation of methylmercury in organisms atop aquatic food webs (Wiener et al. 2003).

Channel reconstruction: Potential changes in bioavailability of mercury. Masses of mercury are large in riverine sediments and overbank soils in parts of the Bay-Delta ecosystem. That mercury, however, may not be readily available for methylation, either because it is not physically located in zones of active methylation or because it has undergone diagenesis to forms with low solubility or low bioavailability. Disturbance of such contaminated sediments may increase the bioavailability of in-place mercury for methylation.

Steelhead and chinook salmon habitat restoration: Potential effects on mercury cycling. The removal of dams or other physical modifications of rivers can affect the transport, distribution, and transformations of sediment-associated mercury. The Upper Yuba River Studies Program, funded by the California Bay Delta Authority, is evaluating the long-term biological, environmental, and socio-economic feasibility of introducing wild chinook salmon and steelhead trout to the Upper Yuba River Watershed. The environmental fate of mercury in gold-mining debris accumulated above the Englebright Dam (a barrier to fish migration) and the bioaccumulation of methylmercury in fish are key issues being examined in that Program (see Attachment F, Water Quality Presentation, at http://www.nasites.com/pam/yuba/documents.asp). The potential effects of disturbing mercury-contaminated, gold-mining debris is also being assessed in conjunction with improvement of fish passage at the Daguerre Point Dam, which is on the Yuba River downstream of the Englebright Dam.

Environmental Justice. The Ecosystem Restoration Program includes environmental justice concerns as a program priority. Ecological restoration in a mercury-contaminated ecosystem could affect methylmercury production, increasing methylmercury contamination of food webs and exposure of biota, including humans. Thus, the issue of methylmercury-contaminated fish also raises concerns about environmental justice, given that certain ethnic and socioeconomic groups of humans can be disproportionately exposed to contaminants in fish via their high rates of fish consumption (National Environmental Justice Advisory Council 2002), a situation considered probable in the Delta and its tributaries.

IV. Development of the Mercury Strategy

Development of a mercury strategy was prompted by the recognized need for an integrated, systematic framework for addressing key management and scientific questions concerning the sources, biogeochemical cycling, effects, and mitigation of mercury in the Bay-Delta ecosystem. It was also recognized that critical evaluation of the effects of ecosystem restoration on mercury cycling and methylmercury exposure would require an integrated approach in an ecosystem of such large scale, dynamic character, and complexity.

Programmatic Guidance

The California Bay Delta Authority's Science Program provided the following guidance regarding the mercury strategy. First, the strategy should include recommendations concerning (1) integrated monitoring of mercury in fish to assess risks to human health and wildlife, (2) holistic investigations that are systematic or process oriented, and (3) locally focused investigations, including remediation at mine sites. Second, the total cost of implementing the strategy should not exceed $7 million to $10 million per year. Third, the strategy should have a duration of 4 years.

In developing the strategy, we have also provided a framework conducive to adaptive management, an iterative learning and management approach used in the California Bay Delta Authority's programs to critically evaluate management actions and to apply both expert advice and the results of research and monitoring to future management actions (Jacobs et al. 2003). The strategy links monitoring and process-oriented research to restoration projects and remedial actions to provide information that can be applied to adaptive management of mercury as restoration progresses. The inclusion of science-based performance measures related to methylmercury exposure and associated risks is, therefore, an important feature of the mercury strategy.

Defining the Problem and Challenge – Unifying Themes for a Science and Management Agenda

Clear definition of the problem(s) affecting ecosystem or human health is an essential first step in an adaptive management process (Johnson 1999*a*). In a toxicological sense, the primary problem with mercury in the Bay-Delta and other aquatic ecosystems can be defined as *biotic exposure to methylmercury*. It follows that an overall challenge to scientists and managers involved with ecological restoration in the Bay-Delta ecosystem is to *avoid increasing – and to eventually decrease – biotic exposure to methylmercury*. Success in meeting this substantial challenge will require rigorous interdisciplinary investigations and strong linkages between science and management. Moreover, this challenge should provide a unifying sense of purpose for participating scientists, ecosystem managers, and other participants, as well as a unifying framework for adaptive management of this mercury-contaminated ecosystem.

Public Input

Two workshops were convened to review pertinent information on the Bay-Delta ecosystem and to obtain public input on the strategy. The first workshop, held on 16-17 September 2002, was devoted largely to a final review of the California Bay Delta Authority project titled "Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed" (Appendix 1). That 3-year project examined patterns of mercury contamination in source areas, sediments, water, fish, and wildlife in the Bay-Delta watershed. The workshop, which had 87 attendees, also included presentations and discussions concerning other ongoing or planned studies of mercury in the Bay-Delta ecosystem and the first public discussion of the mercury strategy.

The second workshop, held on 8-9 October 2002, included (1) an assessment of the state of our knowledge regarding the cycling of mercury in the Bay-Delta and other aquatic ecosystems, (2) the identification of key management questions and goals pertaining to mercury in the Bay-Delta ecosystem, (3) the identification of critical information gaps concerning mercury in the ecosystem, (4) a discussion of potential linkages between ecological restoration projects and mercury cycling in the basin, and (5) a discussion of priority goals and objectives for mercury investigations (Appendix 2). This workshop, which had 93 attendees (Appendix 3), focused on obtaining input from environmental planners, resource managers, scientists, and the public. A series of breakout-group sessions served as the primary pathway for obtaining topical input from workshop participants (Appendix 4).

V. CORE COMPONENTS OF A MERCURY PROGRAM

The framework for the mercury strategy contains six core components. Each core component addresses one or more management goals and includes specific, supporting objectives pertaining to scientific activities (research and monitoring), management actions, or both. Management actions include source remediation, risk communication, ecosystem restoration, and landscape management. The six core components and their associated management goals are as follows.

Core Components	Management Goals
1. Quantification and evaluation of mercury and methylmercury sources	To identify mercury sources that contribute most strongly to the production and bioaccumulation of methylmercury
2. Remediation of mercury source areas	To identify remedial actions that can reduce loadings of mercury from sources to surface waters and decrease the exposure of aquatic biota to methylmercury
3. Quantification of effects of ecosystem restoration on methylmercury exposure	To document and understand the effects of ecosystem restoration in wetland, floodplain, and riverine habitats on the production and bioaccumulation of methylmercury in the Bay-Delta ecosystem
4. Monitoring of mercury in fish, health-risk assessment, and risk communication	To protect human health by assessing and reducing exposure to methylmercury-contaminated fish To provide a "performance measure" to gage methylmercury contamination of the Bay-Delta ecosystem during restoration
5. Assessment of ecological risk	To protect fish and wildlife from adverse effects of methylmercury exposure
6. Identification and testing of potential management approaches for reducing methylmercury contamination	To identify and evaluate potential landscape management approaches for reducing the production and abundance of methylmercury in the ecosystem, as well as the associated exposure of resident biota

This framework incorporates two widely used approaches for reducing exposure to methylmercury: (i) reduction of mercury loadings and (ii) monitoring of mercury in fish as a scientific foundation for providing fish-consumption advice. A third, largely untested approach, management of contaminated landscapes to decrease the *in situ* production of methylmercury, is also included and should be evaluated as a potential means of reducing methylmercury contamination and exposure.

The rationale and objectives for each core component are as follows.

1. Quantification and Evaluation of Mercury and Methylmercury Sources

Mercury loading is one of several factors affecting the production and bioaccumulation of methylmercury in an aquatic ecosystem. Accordingly, a coordinated effort is needed to estimate loading rates of mercury (from all relevant sources) to the San Francisco Bay-Delta ecosystem and to assess the relative contributions of different sources of total mercury and methylmercury to methylmercury exposure. Recent work has shown that atmospheric deposition is the dominant source of mercury in many aquatic ecosystems (Fitzgerald et al. 1998, Wiener et al. 2003). However, few studies have been conducted in ecosystems with the complex array of potentially important sources expected in the San Francisco Bay-Delta ecosystem (e.g., watershed inputs, wet deposition, dry deposition, geothermal, nearby oceanic emissions, discharges from industry and publicly owned treatment works, and a human population exceeding 10 million).

A recent assessment of mercury loads (Foe 2002) has shown that watershed inputs of mercury from the Sacramento and San Joaquin rivers dominate the mercury budget to the Delta, which appears to be a net sink for methylmercury. The riverine inputs of methylmercury to the Delta are also important, but the sources of methylmercury for the Sacramento and San Joaquin rivers – whether exported from tributary streams, produced in bed sediments, or both – are not well known. Quantification of the sources of methylmercury in the Sacramento and San Joaquin river basins would allow amelioration to be focused on the dominant source area(s).

Recent research has shown that the phase, redox status, and ligand chemistry of the various mercury sources can strongly influence the bioavailability of inorganic mercury to methylating bacteria (Benoit et al. 1999*a*, 1999*b*, 2001, Babiarz et al. 2001, Bloom 2003, Drexel et al. 2002, Choe et al. 2003). Moreover, bacteria can assimilate Hg(II) from both uncharged and positively charged species, and different physiological conditions can affect the microbial uptake of Hg (II) (Golding et al. 2002, Kelly et al. 2003). Thus, a mass-accounting approach for total mercury may not necessarily identify the most important source(s) of total mercury from the standpoint of methylmercury production and exposure. The development of strategies for mercury-source assessment is further complicated by the recent discovery that "new" inorganic Hg(II) entering an aquatic ecosystem is more available for methylation (and bioaccumulation) than is "old" mercury present in sediments and soils (Hintelmann et al. 2002, D.P. Krabbenhoft, U.S. Geological Survey, Middleton, Wisconsin, unpublished data). Mercury investigations in the Bay-Delta ecosystem should consider the reactivity and availability of mercury from various sources for microbial uptake and subsequent methylation.

The *primary management goal* for this core component is to identify the mercury sources that contribute most strongly to the production and bioaccumulation of methylmercury. This goal should be supported by the following six objectives. Within core component 1, objectives 4,5, and 6 should receive highest priority.

(1) To quantify mercury pools in the Bay and Delta. A useful exercise in a mass-loading assessment is to consider fluxes in the context of the standing pools of the contaminant of interest. For total mercury, and in some cases for methylmercury, bed sediment is the ecosystem compartment with the largest mass of accumulated mercury. This should be the case in the Bay-Delta, given the historic and continuing inputs of mercury-contaminated sediment. Existing information (e.g., Cappiella et al. 1999, Hornberger et al. 1999, Heim et al. 2003, Slotton et al. 2002*a*) could be used to estimate sedimentary masses of total mercury and methylmercury, although existing data may over-represent open-water sites relative to vegetated environments (Heim et al. 2003, Gill et al. 2002, Slotton et al. 2002*a*) that deserve attention. Moreover, the collection and analysis of sediment cores may be needed to quantify sedimentary inventories of mercury in some areas.

(2) To identify mercury-contaminated sediments within the Sacramento and San Joaquin river watersheds that are susceptible to mobilization by erosion. Assessments in the Cache Creek Watershed – a mineralized and mercury-rich sub-basin of the Sacramento River basin – have

provided a general description of mercury sources (natural deposits, geothermal sources, and mercury-mining wastes) along with estimates of mercury fluxes during low-flow conditions from streams in the sub-basin to the Sacramento River. The Cache Creek watershed is a small fraction of the Sacramento River basin, however, and the remainder of the basin is poorly understood. Vast amounts of mercury (millions of kilograms) were lost during the Gold Rush at mine sites in the Sierra Nevada, yet we are unaware of comprehensive quantitative assessments of residual mercury at the mines, the down-slope piles of mining wastes, the downstream reservoirs, or the alluvial deposits in the Central Valley upstream of the Bay-Delta. Large-scale assessments of this type could be expensive to execute and require considerable funding. A well-designed and coordinated GIS-based approach is, therefore, recommended to derive "bounding estimates" of remaining mercury inventories in the basins, with emphasis placed on mercury-contaminated sediments that could be mobilized by erosive processes. This type of information would greatly aid and facilitate the remedial efforts described in core component 2 below.

(3) To assess the significance of mercury loadings to the Bay-Delta from other sources. Initial estimates of loadings of total mercury and methylmercury to the Bay-Delta, made at the macro scale, showed (i) that external loadings of total mercury are dominated by riverine flow, most notably the Sacramento River, (ii) that a significant fraction of the total mercury flux through the Bay-Delta is derived from resuspension of contaminated sediment, and (iii) that there is a methylmercury sink in the Bay-Delta (Domagalski et al. 2003, Foe 2002, Gill et al. 2002). Additional evaluations should include urban sources (runoff, landfills, and publicly owned treatment works), an expanded network of sites for monitoring mercury in wet deposition (Tsai and Hoenicke 2001), contributions from dry atmospheric deposition (particulate and reactive gaseous mercury), an assessment of inputs from agricultural lands, and internal recycling via processes such as sediment resuspension and deposition within the Bay-Delta.

(4) To identify current key sources and sinks of methylmercury in the Bay-Delta. Tributary streams, wetlands, bed sediments, and flooded soils are likely to be the main sources of methylmercury within the watershed. Gill et al. (2002) and Slotton et al. (2002*a*) showed that wetland soils in the Delta often have higher concentrations of methylmercury than adjoining open-water sediments, and that wetlands can be sources of methylmercury to surrounding waters. Beyond that, the locations and types of existing habitats that support high rates of methylmercury production have not been characterized. Methylmercury concentrations, as a percentage of total mercury, in sediments and soils can be used as a surrogate and integrator of net methylmercury production. Examination of tidal fluxes from different landscape types is another useful tool. Both process-based research and landscape-level models will be needed to address this objective.

(5) To estimate fluxes of total mercury and methylmercury in the tidally influenced Bay-Delta. Assessing mass fluxes within the Bay-Delta system will be an important, but enormously challenging effort because of the system's complex hydrodynamic flow regime (Monismith et al. 2002, Schoellhamer 2002). Sampling strategies for quantifying material fluxes in tidally influenced areas should be designed with input from hydrodynamic specialists familiar with the Bay-Delta Estuary to prevent aliasing, which is defined as the introduction of spurious, low-frequency signals in time-series data that can be introduced by tidal fluctuations.

(6) To evaluate the reactivity and bioavailability (for methylation) of mercury from different sources. Foe (2002) estimated that inputs of total mercury to the Delta from riverine sources are much greater (~100 fold) those from direct atmospheric deposition onto surface waters of the Delta and flooded Yolo Bypass during a wet year. Mercury from indirect atmospheric deposition also reaches the Delta via runoff from the terrestrial catchments, but a lack of information concerning inputs of mercury in dry deposition, watershed retention of atmospherically deposited mercury, and other factors preclude reliable estimates of indirect atmospheric inputs to the Delta. However, larger differences in reactivity or bioavailability (to methylating bacteria) among mercury phases and species in the Bay-Delta are possible, and the relative importance of different mercury sources to formation of methylmercury cannot be ascertained with existing information. Phase and redox speciation of mercury, redox conditions, chemistry of the aqueous environment, sulfur and carbon availability and cycling, and microbial activity all play key roles in determining methylation activity in an aquatic setting (Benoit et al. 2003, Wiener et al. 2003). Initial evaluations in the Bay-Delta ecosystem suggest that the solid-phase chemistry (mineralogy, stoichiometry, grain size, and reactivity) of mercury in mine wastes and stream-bed sediments is quite variable (Bloom 2003). A GIS-based approach would be appropriate for this objective, given that mercury speciation and methylation potential can be expected to vary as a function of both source and receptor areas (Bloom 2003; Figure 3). In short, bioavailability and methylating activity should be considered together when assessing the potential for transformation of mercury from different sources into methylmercury.

2. Remediation of Mercury Source Areas

The *overall management goal* of this core component is to identify remedial actions that can reduce loadings of mercury from sources to surface waters *and* decrease the exposure of aquatic biota to methylmercury. Large amounts of mercury-contaminated mining wastes and sediment are now widely distributed in watersheds that are up-gradient from the Bay-Delta. Information is now available for identifying candidate mercury-mine sites for remediation, based on the estimated total annual export of mercury from a number of sites. It is tempting to assume that the best approach to mitigate the mercury problem in the Bay and Delta is through reduction of total-mercury loads; however, the identification of optimal remedial actions will require a more complete understanding of the relative bioavailability (for methylation) of mercury from different sources. An *optimal remedial action* is defined here as one that will reduce loadings of bioavailable inorganic mercury or methylmercury from source areas, thereby decreasing the abundance of methylmercury in receptor aquatic environments down gradient from the source.

A stepwise approach for the planning, testing, and implementation of remedial actions at mercury-source areas is outlined below. The distribution, mercury masses, and susceptibility for erosive transport of mercury have been characterized for selected mine sites in the Cache Creek Basin (Churchill and Clinkenbeard 2003); therefore, it is recommended that initial remedial planning and pilot projects be focused there. With the availability of additional information, remediation should be considered for other contaminated areas. The overall management goal for this core component should be supported by the following objectives.

(1) To develop a ranking system for prioritizing source areas (mine sites, stream bed and alluvial deposits, and geothermal springs) for possible remediation.

mercury sources where remediation would have the greatest potential for reducing biological exposure to and bioaccumulation of methylmercury in down-gradient aquatic environments. The following variables could be included in the ranking system: (i) potential for erosion of mercury-contaminated substrates (with emphasis on extreme runoff events), (ii) the speciation and reactivity of mercury at the source site, (iii) the size of potentially mobile mercury deposits, (iv) the proximity to down-gradient aquatic environments, (v) the relative methylation potential of down-gradient environments, (vi) the value of biotic resources in down-gradient aquatic environments, (vii) the likelihood for success for any particular site, (viii) cost-benefit considerations, (ix) the availability of existing information, and (x) the perceived scientific benefits of individual sites in providing useful information. These variables could initially be weighted equally, given that we cannot presently predict their relative influence on methylmercury exposure in down-gradient environments.

(2) To identify remedial strategies for reducing the mobilization of mercury to down-gradient environments. Initial emphasis should focus on containing solid and aqueous phases of mercury, although strategies for containment of mercury-rich deposits should be general in nature and seek to minimize volatilization to the atmosphere. Control of erosion should be the main remedial method for containing solid-phase mercury (Churchill and Clinkenbeard 2003). Remedial approaches could include the following: (i) re-vegetation, contouring, and possibly re-location of waste piles, (ii) establishment of settling basins, (iii) routing of mine drainage or storm runoff away from, or around, mercury-rich deposits and calcines at mercury mines (Rytuba 2000) and away from mercury-rich sediments in tunnels and ground sluices associated with hydraulic gold mines (Alpers et al. 2002*a*), and (iv) stabilization of stream banks containing mercury-rich debris. Mercury-enriched liquids include geothermal fluids and ground water that has been in contact with contaminated mine wastes. Depending on site characteristics, geothermal fluids may or may not come into contact with contaminated mine wastes. Relative to eroding mine wastes, geothermal fluids contribute very little mercury to watershed export at the scale of the Bay-Delta ecosystem (Churchill and Clinkenbeard 2003); however, geothermal fluids are locally significant as sources of mercury in some sites, such as Sulfur Creek. Settling basins could be constructed to trap mercury-rich precipitates at geothermal sites, but containment of mercury in geothermal fluids may not be cost effective. Reducing mercury mobilization by soil and ground waters could be accomplished by routing surface runoff away from waste piles and possibly by the use of geo-membranes to retard infiltration.

(3) To implement pilot remediation projects. After completion of objectives 1 and 2 above, pilot projects should be implemented to examine the efficacy of various remedial approaches. Pilot projects conducted at "type" locations could be useful for "scaling up" predictions of reductions in mercury loads at the basin scale, given more intensive remedial efforts. Pilot remediation sites should be representative of "type conditions" (e.g., mine waste piles susceptible to erosion, unstable stream bank deposits near mines, geothermal springs, mine sites discharging into mercury-sensitive areas, mine sites mixed with acid mine drainage, reservoir oxygenation projects, sulfate control projects). Pilot projects should be designed to allow testing of hypotheses related to factors controlling the response to remediation (e.g., slope, grain size, mercury concentration, vegetation cover). To the extent feasible, pilot projects should be linked to other funded or planned investigations, including monitoring of mercury in sentinel fishes,

assessment of mass balances for total mercury and methylmercury, and process studies of mercury cycling.

(4) To identify non-mercury targets for remediation. Factors other than bioavailable mercury may limit the net production of methylmercury in the Bay-Delta ecosystem. In the Florida Everglades, for example, the addition of dissolved organic carbon to experimental mesocosms stimulated more methylmercury production than did addition of either mercury or sulfate alone (David Krabbenhoft, U.S. Geological Survey, Middleton, Wisconsin, unpublished data). The addition of sulfate (without added mercury) can also stimulate methylation (Gilmour et al. 1992, Branfireun et al. 1998). Some mercury sources that do not contribute substantively to mercury loadings, but are important sources of sulfate, may warrant consideration for remedial efforts. Potentially significant sources of sulfate include thermal springs in the Coast Range (Churchill and Clinkenbeard 2003) and acid mine drainage in the Sierra Nevada (Alpers et al. 2002*b*).

(5) To develop and employ performance measures to evaluate the effectiveness of remedial actions. Performance measures should be developed to evaluate the success of remedial actions in reducing (i) mercury loads and (ii) bioaccumulation of methylmercury. Such performance measures could be quantified at various locations down-gradient from remedial sites to estimate the spatial extent of benefits from remedial actions, given that some sites may contribute a small fraction of the mercury load at the basin scale and that benefits would be most evident near the site of remediation. Moreover, priority should be placed on assessing the effects of remedial actions on the abundance of methylmercury, which better reflects the overall goal of source remediation. Performance measures related to bioaccumulation could be accomplished by coordinating sampling and analysis with the monitoring of mercury in sentinel species (core component 4), and should be quantified at various spatial scales.

3. Quantification of Effects of Ecosystem Restoration on Methylmercury Exposure

The *overall management goal* of this core component is to document and understand the effects of restoring wetland, floodplain, and riverine habitats on the production and bioaccumulation of methylmercury in the Bay-Delta ecosystem. Success in achieving this goal will require an understanding of (1) processes and factors affecting the methylation of inorganic mercury and the demethylation of methylmercury, (2) causal linkages between restoration activities and these mercury transformations, and (3) pathways for entry of methylmercury into aquatic food webs.

Some restoration activities (channel reconstruction and dam removal) and remedial efforts (reduction in loadings of mercury and fine sediment) are expected to affect the transport and distribution of sediment and associated (mostly inorganic) mercury. This core component, however, does not emphasize the effects of restoration on the distribution and transport of total mercury in the ecosystem. Load reduction is addressed in core components 1 and 2, and potential effects of dam removal are being addressed in investigations on the Upper Yuba River.

With regard to evaluating potential effects of ecosystem restoration on mercury cycling, we here recommend that highest priority be given to investigations examining effects of restoration on (1) the bioavailability of inorganic mercury for methylation and (2) the microbial production of methylmercury. Given that mercury contamination of aquatic environments is widespread in the Bay-Delta ecosystem, we believe that changes in bioavailability or methylation rates have much greater potential to significantly increase methylmercury exposure in this ecosystem than do changes in the spatial distribution of total (mostly inorganic) mercury. Studies in other aquatic ecosystems show that experimental stimulation of methylation can increase the abundance of methylmercury and its uptake in biota as much as 10- to 20-fold, even in lightly contaminated environments where no mercury was added (Kelly et al. 1997, Hall et al. *in press*).

Accordingly, this core component should focus on those restoration activities, such as wetland restoration and floodplain inundation, with the greatest perceived potential to increase the production and bioaccumulation of methylmercury. Wetland restoration is emphasized, because the areal extent of planned wetland restoration in the Bay-Delta ecosystem is large (CALFED Bay-Delta Program 2000*b*) and restored wetlands may become increasingly significant as sites of methylmercury production and export (Hurley et al. 1995, St. Louis et al. 1996, Sellers et al. 2001). This core component includes the following objectives.

(1) To characterize the biogeochemical cycling of mercury in wetlands, with emphasis on understanding processes and factors controlling the abundance of methylmercury. Process-level investigations of mercury cycling should examine methylation and demethylation in wetlands, and identify pathways for the transport and entry of methylmercury into food webs supporting production of fish and wildlife. This work is needed to identify environmental and trophic (or food-web) factors controlling the net production of methylmercury and the resulting exposure of biota across wetland types in the Bay-Delta system. These studies should identify ecosystem changes resulting from restoration activities (e.g., altered soil and water chemistry, water flow, hydroperiod, and food webs) and determine how such changes affect the production and bioaccumulation of methylmercury, given that a mechanistic understanding is needed for ecosystem management. Relevant indicators of methylmercury production and biotic exposure in wetlands should also be developed. Investigations should be done at multiple spatial scales to assess the extent to which wetland restoration influences the abundance of methylmercury at both local and ecosystem scales.

(2) To determine if the net production of methylmercury and biological exposure to methylmercury vary among existing types of wetlands. Investigations should quantify and compare the net production of methylmercury and biological exposure to methylmercury in existing types of wetlands (agricultural, managed, tidal, and non-tidal) within the Bay-Delta system. If feasible, it would be useful to characterize food-web structure, which can greatly affect methylmercury exposure and accumulation in biota of upper trophic levels. The information obtained should be entered into a geospatial database to facilitate the qualitative ranking of wetland types, sub-habitats, and geographic settings with respect to methylmercury supply and associated biotic exposure. This work should support the eventual development of models relating methylmercury bioaccumulation to wetland type or wetland characteristics that could be used to guide restoration planning.

(3) To document the effects of wetland restoration activities on the abundance and distribution of methylmercury by incorporating process-based investigations and analyses of biosentinel species into restoration projects. Process-level investigations should examine mercury transformations that influence the abundance of methylmercury and quantify the comparative bioaccumulation and trophic transfer of methylmercury in areas affected and unaffected by

wetland-restoration projects. Spatiotemporal variations in methylmercury concentrations in biosentinel species, coordinated with the monitoring of mercury in fish (core component 4), should be statistically examined to assess their relation to ecosystem restoration activities. We define a *biosentinel* as an aquatic organism (e.g., small prey fish or macroinvertebrate) for which analysis provides a reliable, sensitive indicator of the relative abundance of methylmercury in aquatic food webs. Criteria for selection of biosentinel organisms are discussed in section V.4 of this document.

Some projects involving wetland restoration and floodplain inundation – restoration actions with the potential to significantly increase methylmercury production – should be evaluated at the project level. Wetlands can be sites of high rates of methylmercury production and export. Seasonally flooded soils can also be important sites of mercury methylation, particularly on inundated, vegetated habitats where inundation is followed by depletion of dissolved oxygen near or above the sediment-water or soil-water interface.

Two general mercury-assessment approaches are recommended for such projects. The first is to examine on-site effects of restoration actions on the abundance and bioaccumulation of methylmercury. This could include analyses of water, surficial sediment (uppermost 2 to 4 cm), and one or more biosentinel organisms for methylmercury and total mercury in a spatiotemporal sampling framework. The second is to examine potential off-site effects by estimating the mass of methylmercury exported from the restored site to aquatic environments down gradient. From a mass-balance perspective, it would be desirable to obtain comparable estimates of the export of mercury and methylmercury from agricultural landscapes before and after their conversion to functional, restored wetlands.

Such project-level work should be done in collaboration with established specialists having the capabilities to develop an acceptable monitoring program, to accurately characterize baseline conditions, and critically examine and interpret responses to restoration. Atomic fluorescence spectrophotometry is the preferred analytical method for quantifying total mercury and methylmercury in dilute media such as surface water, where concentrations are usually in the nanogram-per-liter or sub-nanogram-per-liter range. Trace-metal-free (clean) techniques should be applied to avoid handling contamination of water samples with mercury concentrations.

(4) To estimate the cumulative contribution of restored wetland and floodplain habitats to the total methylmercury budget for the Delta and Bay. The internal production of methylmercury in all restored areas should be estimated and compared to the external methylmercury budget for the Bay-Delta System. Wetlands may be important sites of methylation, but do they contribute significantly to methylmercury budgets at the scale of the whole ecosystem? This effort should be an iterative process, and estimates should be refined as quantification of external and internal methylmercury production improves.

(5) To estimate the production and bioaccumulation of methylmercury resulting from the use of dredge tailings in habitat restoration. The use of dredged gravels has been proposed for an array of applications in restoration projects: to fill gravel pits in the flood plain, to line ponds or wetlands, or to inject gravels into streams to enhance spawning habitat for fish. The speciation of the mercury in these contaminated tailings and its availability for methylation and uptake by aquatic biota are unknown, hampering critical evaluation of the potential consequences of using

these materials in restoration projects. Most of the mercury in these gravels is associated with fine-grained material (Ashley et al. 2002), which could be mobilized during use of gravels in aquatic restoration efforts, potentially affecting loadings of mercury and methylmercury in downstream areas.

We recommend that the California Bay Delta Authority sponsor a study to assess the potential impacts of using these contaminated dredged gravels in restoration. The concentration and speciation of mercury in dredge-tailing gravel to be used in restoration projects should be characterized. Projects that will use or disturb large amounts mercury-contaminated dredge tailings should include a monitoring component to assess the effects on the abundance and bioaccumulation of methylmercury.

The Dredge Tailings Workgroup, which is affiliated with the Delta Tributaries Mercury Council (contact, Carol Atkins), is discussing issues concerning mercury associated with dredge tailings and the use of the tailings in restoration. This working group could be a valuable source of information and guidance in planning research and monitoring activities to assess impacts of using dredge tailings in restoration projects.

4. Monitoring of Mercury in Fish, Health-Risk Assessment, and Risk Communication

The consumption of fish and other aquatic organisms is the primary pathway for human exposure to methylmercury. A regional program for monitoring mercury concentrations in fish should, therefore, be in effect during ecosystem restoration. The *first management goal* of this core component is to protect human health by quantifying methylmercury contamination of fish, by assessing human exposure to methylmercury, and by developing and communicating advice for reducing exposure to methylmercury, the dominant form of mercury in fish. Accordingly, this core component should include the identification of groups with high methylmercury exposure, as well as provision of outreach and education to reduce exposure. Goal 1, which focuses on the protection of human health, should include the following objectives.

(1) To monitor concentrations of total mercury (present largely as methylmercury) in sport fish eaten by humans. Monitoring should identify fish, shellfish, and other aquatic biota consumed by humans that contain mercury concentrations exceeding criteria for protection of human health. Monitoring should also identify fish with low concentrations of methylmercury that can be safely eaten, provided that concentrations of other bioaccumulative contaminants of concern in the Bay-Delta ecosystem (e.g., polychlorinated biphenyls and dieldrin) are not problematic.

(2) To assess health risks of fish consumption to humans. Health-risk assessment should focus initially on existing data on mercury in fish, shellfish, and other edible aquatic biota and should incorporate new data as results from (future) monitoring become available. Considerable information on mercury contamination of fish from the Bay-Delta ecosystem has been obtained during the past 5 years, and workshop participants viewed the interpretation of existing data on mercury in edible fish tissue as a clear and immediate need. Moreover, health-risk assessment would be greatly facilitated by the development of an effective data management system, which is urgently needed for storage and retrieval of existing and future fish-tissue data. This data management system should be used for data on mercury and other contaminants in fish; it should also accommodate information related to angler demographics and fish harvest (from creel

surveys), as well as data from focused investigations related to health-risk assessment and risk communication (objective 5 below).

(3) To develop fish-consumption advice for the public. The provision of fish-consumption advice or advisories (U.S. Environmental Protection Agency 2003) can be effective for reducing the exposure of humans to methylmercury, even within a 2-year time frame (Lucotte et al. 2003). Fish-tissue data on mercury from prior surveys and future monitoring efforts should be analyzed to determine if a single regional fish-consumption advisory is appropriate or whether spatial variation in contamination of fish warrants multiple advisories across the region.

(4) To conduct outreach and education to increase public awareness of methylmercury contamination of fish and the health risks of methylmercury exposure. The public benefits of this core component would be enhanced by active outreach and education to increase public awareness of methylmercury contamination of fish, as well as the health risks of methylmercury exposure. Analyses of existing and future (monitoring) data on mercury in edible fishes, combined with information from focused investigations (objective 5 below), can be used to identify priority areas and target groups for outreach and education efforts. The health benefits of eating clean fish (e.g., Egeland and Middaugh 1997) should also be communicated.

(5) To perform essential, focused investigations needed to support health-risk assessment and risk communication. Focused investigations are needed to (i) estimate rates and patterns of fish consumption, (ii) identify and characterize groups with potentially high levels of exposure to methylmercury, (iii) assess the public's information needs and concerns relating to consumption of contaminated fish, (iv) identify optimal methods for communicating advice, and (v) evaluate the effectiveness of fish-consumption advisories. The findings of these focused investigations should guide outreach and education activities targeted to reduce human exposure to methylmercury.

We recommend that from 70 to 80 percent of the resources allocated to this core component be devoted to the objectives under Goal 1. Moreover, it is re-emphasized that activities under objectives 2 through 5 above should not await data from the fish-monitoring effort. The most effective approach for reducing methylmercury exposure in humans – within the short (4-year) time frame encompassed by this mercury strategy – is to identify and work with methylmercury-exposed groups to reduce their consumption of contaminated fish.

The *second management goal* of the monitoring program would be to provide a "performance measure" to gage methylmercury contamination of the Bay-Delta ecosystem as ecological restoration proceeds. Many factors can influence the bioaccumulation of methylmercury in long-lived biota of upper trophic levels, greatly complicating the detection and interpretation of patterns in mercury concentrations in large game fishes. A biosentinel-based monitoring approach is, therefore, preferable for gaging methylmercury contamination of aquatic food webs and for detecting spatial and temporal patterns in contamination during restoration.

A biosentinel species should possess certain key attributes. It should be spatially widespread and abundant throughout much of the ecosystem. Ecotoxicological relevance is enhanced if the biosentinel is important in the food-web transfer of methylmercury in the studied ecosystem. The biosentinel should exhibit limited variation in diet and trophic position; in other words, variation in mercury concentrations in the biosentinel should result largely from variation in processes influencing the abundance of methylmercury in the aquatic ecosystem, rather than to differences in diet or trophic position. Small whole fish, such as 1-year-old yellow perch (*Perca flavescens*), have been widely used as a biosentinel of methylmercury contamination of food webs in temperate lakes in the United States and Canada (Frost et al. 1999, Wiener et al. 2003). During their first year, yellow perch occupy a low trophic position, feeding on zooplankton and small zoobenthos, yet small yellow perch are regionally important in methylmercury transfer in food webs supporting sport fish, piscivorous wildlife, and humans who consume sport fish. Age-1 perch are also sensitive indicators of annual and spatial variation in the abundance of methylmercury in aquatic food webs (Frost et al. 1999). Potential biosentinel organisms could also include certain young-of-the-year fishes, aquatic invertebrates, and the eggs of certain aquatic birds.

Goal 2 should include the following two objectives.

(6) To monitor total mercury in biosentinel species to assess methylmercury contamination of aquatic food webs. Sampling and analyses of biosentinel organisms would provide a direct measure of methylmercury concentrations in aquatic food webs supporting production of fish and wildlife.

(7) To identify spatial and temporal patterns in methylmercury concentrations in bioindicator organisms. Spatiotemporal patterns in mercury contamination of biosentinel organisms should be statistically examined to assess their possible relation to ecosystem restoration activities or other potential causal factors. The sampling design should, therefore, include monitoring sites in the vicinity of wetland restoration projects.

The biosentinel approach could also be used to examine the influence of selenium on the abundance of methylmercury in food webs in the Bay-Delta ecosystem. Parts of this ecosystem, such as the San Joaquin River, are notably contaminated with selenium, which can inhibit the production of methylmercury and decrease its bioaccumulation in the food chain. The influence of selenium on the production and bioaccumulation of methylmercury in the Bay-Delta system could be assessed in part by the comparative analysis of selenium and methylmercury in biosentinel organisms and other environmental samples from areas that vary in the abundance of selenium. Linkage of selected mercury investigations to ongoing studies of selenium biogeochemistry in the Bay-Delta system would be a unique, cost-effective opportunity to examine interactions between selenium and mercury.

The monitoring of mercury in sport fish and biosentinel organisms would provide complimentary information on methylmercury in aquatic food webs. Analysis of sport fish would yield data useful for assessing potential dietary exposure in humans who eat fish. The confounding effects of spatiotemporal variation in the diet and trophic position of many sport fishes, however, can diminish their sensitivity for detecting spatial and temporal patterns in the abundance of methylmercury (Wiener et al. *in press*). The analysis of biosentinel organisms, such as small prey fish (preferably of nearly uniform age), would provide a more sensitive indicator of methylmercury concentration in aquatic food webs. Concentrations in a prey-fish biosentinel would be a useful indicator of relative methylmercury levels in food webs supporting production of sport fish, and would be expected to reveal both inter-annual and spatial differences in the supply of methylmercury (Wiener et al. *in press*).

Monitoring data would not – in the absence of other supporting information – conclusively demonstrate cause-and-effect associations. The interpretation of data from a monitoring program should be strengthened by linking monitoring efforts to investigations of ecological and biogeochemical processes or factors that affect the abundance of methylmercury, as well as its bioaccumulation and trophic transfer in aquatic food webs.

5. Assessment of Ecological Risk

Methylmercury is a potential threat to organisms in upper trophic levels of aquatic food webs in mercury-contaminated ecosystems. In birds and mammals, methylmercury in reproducing females readily passes to the developing egg or embryo, and the early developmental stages are much more sensitive than the adult to methylmercury exposure (Scheuhammer 1991, Wiener et al. 2003). Avian reproduction can be impaired in females fed diets with concentrations of methylmercury that are one-fifth of the threshold dietary concentrations causing overt toxicity in adult birds of the same species (Scheuhammer 1991).

A number of bird species that nest or feed in the Bay-Delta may be sensitive to methylmercury exposure (Heinz 2003, Schwarzbach and Adelsbach 2003). Concentrations of total mercury (probably present as methylmercury) in six failed eggs of the federally endangered clapper rail, taken from the central San Francisco Bay, averaged 0.81 µg/g wet weight and ranged from 0.60 to 1.06 µg/g (Schwarzbach and Adelsbach 2003). Methylmercury concentrations of 0.8 µg/g wet weight or greater in eggs adversely affected embryo survival in controlled, egg-injection experiments with eggs of clapper rails (Heinz 2003). Diminished reproductive success could have adverse population-level consequences for clapper rails and other species of wildlife and fish exposed to high levels of methylmercury in the Bay-Delta ecosystem.

The decision process for adaptive restoration of the Bay-Delta System will require information on methylmercury exposure, bioaccumulation, and associated ecological effects in fish and wildlife. Estimates of exposure thresholds associated with reproductive effects in species of concern, based on methylmercury concentrations in tissues or the diet, are currently lacking but would provide biologically relevant targets applicable to adaptive management and environmental decisions. Information in exposure thresholds could also be used to identify those species that are most vulnerable to methylmercury (in terms of sensitivity and exposure) and to assess whether existing levels of methylmercury exposure in the ecosystem could impair recovery of at-risk native species.

The *overall science goal* for this core component is to quantify methylmercury exposure and to assess the likelihood that adverse ecological impacts are occurring or may occur in fish and wildlife as a result of methylmercury exposure. The *overall management goal* is to protect fish and wildlife from adverse effects of methylmercury exposure. Success in achieving this mercury-specific management goal would directly support the California Bay Delta Authority's strategic restoration goals concerning the recovery of at-risk native species and the rehabilitation of the Bay-Delta to support native biotic communities. To achieve this specific management goal, investigations in this core component should be linked to those in core components 2 (remediation of mercury source areas), 3 (quantification of effects of ecosystem restoration on methylmercury exposure), and 6 (identification and testing of potential management approaches for reducing methylmercury contamination).

Laboratory and field studies should examine biological endpoints that are pertinent to assessing effects of methylmercury exposure at the population level. Moreover, guidance from specialists in risk assessment at the outset of research will enhance the utility of information from these ecotoxicological investigations. This core component contains the following two objectives.

(1) *To determine the toxicological significance of methylmercury exposure in wildlife and fish, with emphasis on reproductive effects.* Evaluation of the toxicological effects of methylmercury in fish and wildlife should focus on reproductive endpoints, such as embryo survival (Heinz 2003) or spawning success (Hammerschmidt et al. 2002, Drevnick and Sandheinrich 2003), because of their high sensitivity to methylmercury and relevance to assessing population-level effects. Threshold concentrations of methylmercury (in the tissues or diet) associated with impaired reproduction or other adverse effects in developing young should be estimated.

Dose-response relations and threshold concentrations for reproductive effects should be estimated with controlled laboratory experiments, such as egg-injection studies for birds (Heinz 2003) or controlled dietary exposures (Heinz and Hoffman 2003). Field studies of wildlife should quantify methylmercury exposure in a range of habitat and restoration settings in the Bay and Delta. New and existing dose-response information from experimental studies should be compiled to develop an adequate data base for extrapolation to a variety of pertinent native species in the Bay-Delta System, and field studies should be designed to investigate subtle effects reported in laboratory experiments. For birds, information from the laboratory and field studies by Heinz (2003) and Schwarzbach and Adelsbach (2003) should be used to select species and populations for further investigation. Field and laboratory investigations should be closely linked. The species used in laboratory experiments should match those studied in the field, and the range of methylmercury exposures in laboratory studies should include the range observed in the Bay-Delta ecosystem.

Information on the combined effects of methylmercury and selenium may be needed to fully assess reproductive effects of contaminant exposure in the Bay-Delta ecosystem, which is also contaminated with selenium. Adverse reproductive effects on developing mallard embryos exposed experimentally to methylmercury via the maternal diet, for example, were much greater when selenomethionine and methylmercury were administered jointly than when methylmercury was added without selenium (Heinz and Hoffman 1998).

(2) To identify habitats, areas, and trophic pathways associated with elevated, potentially harmful methylmercury exposure. Habitats, areas, and trophic pathways in the Bay and Delta that are associated with the bioaccumulation and biomagnification of methylmercury to elevated, potentially harmful concentrations should be identified. For birds, the information from recent studies by Heinz (2003) and Schwarzbach and Adelsbach (2003) could be used to select species, populations, and associated foraging sites for investigation. This work should focus largely on evaluating pathways of methylmercury exposure in at-risk, native species of fish and wildlife that are of special concern to resource managers. Bioaccumulation in species of special concern should be linked to sources of methylmercury in field settings, to identify dietary sources of

methylmercury and trophic pathways, habitats, and areas associated with high organismal exposure to methylmercury. Habitats and areas associated with high methylmercury exposure should be identified, characterized, and prioritized with regard to ecological risk. It would be desirable to link some of this work to (already funded) process-level investigations that are examining the microbial production of methylmercury and its entry and subsequent transfer in aquatic food webs supporting production of fish and wildlife.

6. Identification and Testing of Potential Management Approaches for Reducing Methylmercury Contamination

The *overall management goal* of this core component is to identify and evaluate potential landscape management approaches for reducing the production and abundance of methylmercury in the ecosystem, as well as the associated exposure of resident biota. Process-oriented results from core component 3 (Quantification of Effects of Ecosystem Restoration on Methylmercury Exposure) and other mercury investigations studies should be used to identify potential landscape management approaches for consideration. Specific objectives needed to achieve this goal are as follows.

(1) To develop an empirical understanding of processes and habitat factors affecting methylmercury production and exposure. This work should focus on wetlands and tidal flats in the Bay and Delta and should use information from other ecosystem investigations in conjunction with information from the Bay and Delta (from core component 3).

(2) To develop models for predicting effects of specific management scenarios on methylmercury production and export. Initial models could be based on empirical information, but efforts should eventually evolve toward development of process-based, numerical models. Various model types and spatiotemporal scales should be explored, including spatially explicit landscape models. A GIS database (with new and existing data) should be developed to map, classify, and rank wetland types, sub-habitats, and geographic setting with respect to methylmercury supply and biotic exposure.

(3) To determine which of the factors controlling methylmercury production and exposure can be managed in the Bay-Delta ecosystem. This is a crucial link between management and science. What controlling factors can be realistically manipulated without unacceptable consequences? Potential management scenarios should be identified and evaluated as pertinent information becomes available. Examples of potential scenarios include the siting of marsh restorations, the control or diversion of mercury and sediment loads (especially from sources with high bioavailability), and the alteration of vegetation or water flow and hydroperiod. The potential utility of such manipulations should be initially considered in relation to logistical feasibility, cost, potential decreases in methylmercury production, and effects on habitat quality.

(4) To test candidate landscape management approaches in pilot studies to assess performance with regard to methylmercury production, biotic exposure, and bioaccumulation. Potential landscape-management approaches should be tested to assess performance. Initial experimental manipulations could be done at the mesocosm scale. To the extent feasible, larger scale tests should be linked to ongoing process studies and to monitoring of biosentinel organisms to evaluate performance.

Linkages and Integration among Core Components

The mercury strategy, as outlined here, is an integrated program with strongly interconnected components (Figure 4). The interactions include linkages between scientific activities (research and monitoring) and linkages between scientific investigations and management actions (risk communication and education, source remediation, ecosystem restoration, and landscape management). The evaluation of outcomes is also an important feature of the strategy. Scientific investigations, management actions, and evaluations within a given core component should be strongly linked, and these activities should be continuous, rather than sequential. These linkages, which form the basis for adaptive management of mercury in the ecosystem, are utterly crucial for meeting the goals and objectives outlined for the strategy and for providing timely scientific input for adaptive management. The authors of this document contend that the scientific merit, rigor, cost-effectiveness, and overall worth of a mercury program in the Bay-Delta ecosystem will increase in proportion to the strength of such linkages.

The linkages among core components of the mercury strategy are illustrated in Figure 4, where shaded arrows represent the flows of information and interactions that are needed to support decision processes for refinement of scientific investigations and for adaptive management of mercury in the ecosystem. Science is an integral and ongoing tool in adaptive restoration and management; new information gaps will arise as existing gaps are filled, and ongoing evaluation is a key element of adaptive management.

VI. MANAGEMENT OF A MERCURY SCIENCE PROGRAM

The global scientific effort on mercury has produced rapid advances and several landmark discoveries in the past decade (Wiener et al. 2003). Recent scientific progress in the Bay-Delta ecosystem has also been substantial, and increasingly powerful analytical tools and approaches are becoming available for addressing scientific and management questions concerning mercury in the ecosystem. A mercury program would catalyze substantive advances in understanding of mercury cycling and its effects in the Bay-Delta ecosystem, an ecosystem of national importance and renown. The decision-making arena for management and restoration of this ecosystem is expected to be rigorous, and funded projects should meet high standards of reliability, scientific defensibility, and productivity.

The impressive recent progress notwithstanding, critical information gaps remain and much of substance needs to be learned regarding the behavior of mercury in this ecosystem, the risks posed to resident biota and humans, and the steps that can be taken to address the problem. Mercury pollution in the Bay-Delta ecosystem represents an enormous challenge for science and ecosystem management. Managers attempting to reduce methylmercury exposure in this ecosystem must contend with a highly complex biogeochemical cycle, overlain on an ecosystem characterized by enormous complexity, large scale, and pronounced spatiotemporal dynamics. An interdisciplinary effort will be needed to implement this strategy and to apply the new information produced towards adaptive management of the Bay-Delta ecosystem. Many of the core components recommended in section V of this document would require multidisciplinary teams of scientists, as well as the sustained involvement of the appropriate environmental planners and resource managers.

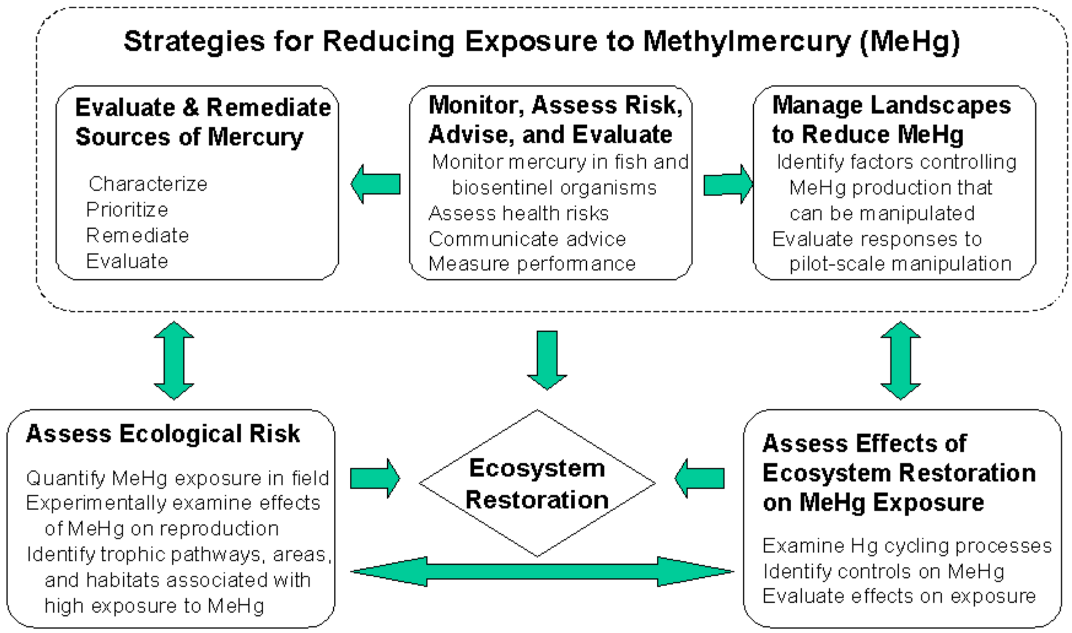

Figure 4. Conceptual model of linkages among components of the mercury strategy. Arrows represent linkages among components of the strategy, where information should flow to provide adaptive feedback for refinement of both scientific and management actions. For simplification, strategy components 1 and 2 (both related to mercury sources) were combined into the single cell on the upper left-hand corner of the figure.

Recommended Approaches for Allocation of Program Funding

Competitive Proposal Review and Selection Process. The competitive Proposal Solicitation Package process used by the Ecosystem Restoration Program is an appropriate mechanism for allocating scientific effort to most of the core components of the mercury strategy outlined in section V of this document. An exception is core component 4, "Monitoring of Mercury in Fish, Health-Risk Assessment, and Risk Communication," for which the competitive proposal process is not considered optimal. The competitive proposal process would, however, be appropriate for part of this core component; that is the focused investigations needed to support health-risk assessment and risk communication (goal 1, objective 5). Detailed recommendations for developing an effective monitoring program are presented in the next subsection.

Requests for proposals should encourage the development of collaborative interdisciplinary proposals by multidisciplinary teams of investigators. In addition to judging scientific merit and relevance to ecosystem management, the proposal review and selection process should include critical evaluation of the scientific stature, leadership skills, and managerial experience of the leading principal investigator (and project manager, if applicable) on prior large projects, as well as the experience and effectiveness of co-investigators as team members on large multidisciplinary projects. The roles and responsibilities of individual team members should be clearly described in project proposals. Team members should have demonstrated skill and expertise in their individual areas of technical responsibility on the proposed work, as well as a track record of timely reporting of findings in refereed papers with coauthors from multiple institutions.

The proposal evaluation process should also include critical evaluation of the composition of project teams. Other large "mercury" research programs have shown that an interdisciplinary approach is essential for understanding the effects and behavior of mercury at the ecosystem scale. Project teams should contain the full range of expertise needed to ensure defensible study design, analyses, and interpretation of data. We recommend that, on average, about half of the team members on a project be "mercury specialists" and the remainder be scientists who bring other, appropriate expertise and knowledge on ecosystem processes (e.g., hydrology, microbial ecology, biogeochemistry, trophic ecology), organismal biology, wetland ecology, sampling design, statistical analysis, modeling, or other pertinent applications. It is essential that mercury specialists work in collaboration with scientists and managers who are knowledgeable about the Bay-Delta ecosystem. Projects estimating mass budgets for mercury or other material constituents in the tidally influenced Bay-Delta, for example, should involve hydrodynamic specialists in the design of sampling strategies. Scientific projects should also involve external scientists who can bring new perspectives, approaches, and analytical capabilities to the team, such as the use of stable-isotope techniques (Hintelmann et al. 2002) to examine the cycling of mercury in the Bay-Delta ecosystem.

Project proposals should demonstrate earnest commitments by team leaders and key team members to provide timely information to ecosystem managers and to participate actively in the application of project results to adaptive management of the ecosystem. Beyond the project level, proposals should reflect willingness by lead investigators to participate substantively in interdisciplinary syntheses of findings from multiple projects. Project budgets should delineate and include the estimated costs for time and travel associated with such efforts.

Development of a Monitoring Program for Mercury in Fish. The establishment of a systematic monitoring program for mercury in fish was considered a high-priority goal by scientists and managers alike. The development and design of an effective monitoring program – capable of achieving multiple objectives (section V, core component 4) – will be a substantial endeavor, requiring insightful leadership, input from managers, multidisciplinary technical guidance, and modest budgetary support. The Proposal Solicitation Package process is not an optimal approach for developing a monitoring program for mercury in Delta fishes. We recommend that a monitoring program be developed in a step-wise fashion, as outlined below, with informed input from leading scientists, risk-assessment and environmental health specialists, fish biologists, resource managers, and other end-users of the monitoring data along the way.

(1) *Establish a multidisciplinary, multi-institutional steering committee to lead and facilitate the developmental process* – This committee should include representatives from appropriate resource management, health, regulatory, and scientific groups. It is also desirable to include representatives with knowledge of environmental justice concerns related to consumption of contaminated fish from the Bay-Delta ecosystem.

(2) *Refine goals and objectives* – Refinement of the goals and objectives identified at the mercury strategy workshop (summarized in Section V, core component 4) is an essential early step in development, needed to ensure that the monitoring program is designed at the onset to address the information needs of health agencies, resource managers, regulatory entities, and other end users. Local representatives (beyond scientific and ecosystem management groups) should be given the opportunity to provide input during the development of the monitoring program, particularly on the choice of fish species and tissues to be analyzed and the areas to be sampled. Peer review of refined goals and objectives is strongly encouraged at this stage.

(3) *Develop robust sampling strategies* – Statistical expertise in sampling design and statistics should be applied to develop robust sampling strategies capable of meeting defined objectives. Statistical analyses of recent, reliable fish-mercury data should be used in crafting an efficient sampling design. As a mechanism for linking monitoring and research, some monitoring sites for biosentinel species should be co-located with detailed process-oriented studies of mercury methylation, bioaccumulation, and food-web transfer. To the extent appropriate and feasible, the sampling of fish for mercury should also be coordinated with sampling of fishes being done for other bioaccumulative contaminants of concern (e.g., PCBs, organochlorine pesticides, and selenium) that may affect fish-consumption advice in this ecosystem. Such coordination would reduce duplication of sampling and sample-processing effort.

(4) *Develop detailed procedures for program tasks* – Protocols should be developed for each of the following: sampling of fish, handling and analyses of samples, quality assurance and quality control, archiving of samples (if warranted), management of data, statistical analysis of data, synthesis and reporting of information, risk communication, public outreach and education, and periodic peer review of all aspects of this core component by an expert panel. The protocols for sampling and analysis of sport fish (objective 1 of core component 4) should meet the requirements of the California Office of Environmental Health Hazard Assessment, to ensure that the data can be used to assess health risks and to issue state fish-consumption advice.

(5) *Subject the sampling frame, methods, and detailed procedures to external peer review and incorporate appropriate revisions*.

(6) *Issue contracts to implement the monitoring program* – The California Bay Delta Authority should contract the mercury-monitoring tasks to a scientific team that is experienced in the sampling and analysis of fish for mercury, with proven capabilities in the management, statistical analysis, and rigorous interpretation of large data sets and a track record of timely reporting of findings from large multidisciplinary projects on mercury. Moreover, the team members should have the institutional support needed for a sustained commitment to at least a 4-year monitoring

program. Contracts should be issued with minimal delay to allocate funds for initiating and accomplishing program tasks.

The California Bay Delta Authority should provide fiscal support for steps 1-5 above. The provision of in-kind support from involved state and federal agencies in all aspects of development and execution is encouraged throughout the monitoring program. Information and knowledge obtained in prior surveys and existing mercury-monitoring efforts within the Bay-Delta ecosystem should be applied in developing the monitoring program, but development and implementation should not be impeded by integration with other monitoring efforts.

The monitoring program should be adaptive, with the flexibility to evolve in response to new knowledge and the changing needs of management, health, and regulatory entities. In this regard, the steering committee is encouraged to consider the operational structure and adaptive process used in managing the Regional Monitoring Program for the Bay as a model for managing this new monitoring program. After initial program development, the steering committee's role could include (1) the facilitation of communication between managers and scientists, (2) consideration of proposed modifications to increase program efficiency and to ensure responsiveness to the evolving needs of information users, and (3) the coordination of peer reviews.

A mercury-monitoring program for sport fish and biosentinel species would provide important information for mercury-related research and remediation projects in the Bay-Delta, providing information essential for reducing human exposure to methylmercury as well as critical feedback for habitat restoration efforts. As such, the development and implementation of a monitoring program should be expedited to the greatest extent possible. Local institutions have expressed enthusiastic support for a regional, adaptive mercury-monitoring program and have demonstrated the technical capability to conduct a state-of-the-science monitoring effort.

Communication, Management and Sharing of Data, and Integration of Findings

An implemented mercury program will produce large amounts of data, and open communication of data and results among participating scientists, agencies, stakeholders, and the public are vital for successful adaptive management and for sustaining political support for the program (Johnson 1999*b*). The synthesis, transfer, and sharing of information from ongoing and recently completed investigations should be actively facilitated, given the importance of rigorous interdisciplinary interpretation and the need to provide timely information for adaptive management. The typical lag times from generation of scientific data until final reporting and publication are long, relative to the anticipated rapid pace of scientific discovery and generation of new information in a mercury program of this scale. Effective mechanisms for rapid sharing of interim results among teams and for information transfer to ecosystem managers, other stakeholders, and the public will be essential to ensure that interim data and information are available to facilitate timely information synthesis, risk analysis, and risk communication. To encourage the exchange of interim results, it is recommended that ground rules be developed for the sharing of data among teams and for the public release of data and findings. We recommend that interim data and products be summarized on a protected website and that listings of existing and forthcoming products be maintained to facilitate the synthesis of findings among teams.

Much routine communication and information exchange can be facilitated with electronic bulletin boards and web sites.

Actively participating scientists and managers should meet at least twice annually to share, discuss, and interpret information from ongoing mercury investigations. It is *essential* that participating scientists and managers meet informally in small subgroups to share and discuss new findings, to identify shortcomings of ongoing projects (enabling mid-course improvements), to plan and coordinate the next year's work, as well as plans for manuscripts and other products. The primary goal of these informal meetings should be to synthesize results at the project and multi-project scales. Cohesion within and among participating teams of scientists would be enhanced by the development and discussion of sets of testable, scientific hypotheses that are fundamental to the Bay-Delta ecosystem. The extent to which funded projects are collectively addressing such ecosystem-scale hypotheses should be assessed. One such hypothesis, for example, could be that "Movement of bioavailable mercury from contaminated sites controls the current concentration of methylmercury in fish in the Bay-Delta ecosystem."

The development of mechanistic models pertaining to the behavior of mercury in parts of the ecosystem, such as the Delta, could also enhance cohesion and synthesis among scientific teams. Model development would stimulate discussion of model-information requirements, leading to identification of important information gaps and the possible focusing of subsequent efforts. Modeling should also incorporate new findings as research and monitoring progress, and serve as a focal point for the synthesis and discussion of results. To be effective, such a modeling effort would need support from the California Bay Delta Authority or other program partners.

Important new findings and progress should be communicated and discussed annually in a formal, public meeting attended by participating scientists, ecosystem managers, program partners, external technical reviewers, and other stakeholders. A technical review of funded mercury investigations should be a key feature of the formal annual meeting. It is recommended that an external science review panel with at least four or five renowned specialists be established at the beginning of the funding period to serve throughout the anticipated, multi-year effort. The panel should be technically diverse, with the collective ability to critically evaluate work in each of the following topical areas: microbial ecology, ecology and hydrodynamics of estuarine ecosystems, biogeochemistry and ecology of wetlands, environmental biogeochemistry of mercury, bioaccumulation and ecotoxicology of mercury, risk analysis, and risk communication. The panel should also include at least one person with substantial knowledge of, and experience working in, the Bay-Delta ecosystem. The external review process should provide critical evaluations at both the project and multi-project (mercury program) levels.

Several participants at the mercury strategy workshop expressed a desire for a formal process of communication among scientists, engineers, and managers to implement adaptive management (Appendix 2). Such a process could link decisions on ongoing restoration efforts to information from ongoing or recently completed investigations. Moreover, it was suggested that resource agencies involved with species of concern, restoration of fisheries, sediment supply, water quality, land use, water management, and reuse of dredged sediments participate in the process.

Coordination

Effective coordination will be absolutely crucial to the success of this overall effort. It is, therefore, highly recommended that the California Bay Delta Authority recruit or appoint a full-time "mercury coordinator" to serve as a scientific leader, a facilitator, a communicator, and a point of contact on mercury issues for the Bay-Delta Program. The coordinator should have the leadership ability, scientific stature, and communication skills needed for effective synthesis and communication. The coordinator should have a key role in the organization and oversight of annual reviews and subgroup meetings. Other recommended duties of the coordinator include participation in the selection of competitive proposals, oversight of quality-assurance efforts (discussed below), presentations to program partners and stakeholders, and participation in the synthesis and reporting of ecosystem-scale findings for publication in primary journals. The coordinator could serve as the key point of contact to the Abandoned Mines Workgroup, the Delta Tributaries Mercury Council (http://www.ice.ucdavis.edu/hg/), the Environmental Justice Subcommittee, and the array of partner institutions involved with environmental health, environmental management, and ecosystem restoration. It is further recommended that the coordinator not be significantly burdened with other assignments, so that Bay-Delta mercury investigations and associated issues can be his or her primary concern.

Quality Control and Quality Assurance

Program Level. Procedures for programmatic oversight of quality assurance should be in place at the onset of a mercury program to define the comparability of data from the participating research groups and to aid responsible use of the information by managers and stakeholders. Quality assurance is essential in a mercury program, because of the overall difficulty in accurately quantifying relevant species of mercury, especially methylmercury, in dilute media with concentrations at the sub-nanogram per liter (part-per-trillion) level. Institutionalized oversight at the program level is needed to address two quality-assurance challenges: (1) to establish confidence that the data produced by multiple laboratories are comparable, and (2) to demonstrate the validity of data for future use and interpretation.

There are many potential components to a robust quality control and quality assurance program, including inter-laboratory comparisons (i.e., blind, round-robin exchange of samples), analyses of split samples from the field, on-site laboratory assessments, estimation of method detection limits, validation of data by third parties, and technical review of methods used for the handling, preparation, and analyses of samples. Inter-laboratory comparisons, which are particularly useful for documenting inter-laboratory precision, should be conducted annually or biannually for the duration of the project. Blind certified reference materials can be used in inter-laboratory comparisons to document and quantify both precision and accuracy (bias). An effective quality-assurance program enhances the confidence of participating research teams and provides quantitative documentation of the precision, accuracy, and comparability of the data collected. About 5 to 10 percent of the annual analytical workload in a project should be devoted to quality assurance at the programmatic level.

Project level. The effort devoted to quality control and quality assurance at the project level should equal or exceed that done at the program level. Quality control and quality assurance activities should be designed to evaluate both field and laboratory methods. Project-level procedures or material to be evaluated should include the collection, handling, preservation, and preparation of samples, as well as chemical reagents, instrumentation, analyses, and documentation. About 10 to 20 percent of the total analytical workload in a project (including field replicates and laboratory splits of samples) should be devoted to quality assurance at the project level.

A Look Ahead

It is unlikely that all of the goals outlined in this Mercury Strategy can be fully met within a 4-year time frame, based on the authors' experience with mercury investigations in a diverse array of ecosystems. Marked advances in understanding of the mercury problem in the Bay-Delta ecosystem should be made during 4 years of intensive, coordinated investigations. Substantial progress should be concomitantly made toward identifying management approaches for reducing methylmercury exposure in this ecosystem.

A 4-year timeframe is, however, admittedly brief for answering all of the pertinent questions, given the extraordinary complexities of the Bay-Delta ecosystem and the mercury problem at hand. Thus, a continuing need for additional scientific work, more narrowly focused and smaller in scale than the effort outlined in this document, should be recognized at the onset. In closing, we therefore recommend that progress in achieving the goals outlined in this strategy be jointly assessed by participating scientists, managers, and stakeholders at the end of the 4-year period, perhaps as the focal point of a dedicated symposium or workshop. The eventual reduction of methylmercury exposure and of mercury-related risks in the Bay-Delta ecosystem can be expected to require continued attention to key information gaps and the institutional refocusing of scientific and management efforts.

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Appendix 1. Agenda for the first mercury workshop, which included (1) the final review of the project titled "An Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed," (2) descriptions of two future mercury projects to be funded by the California Bay Delta Authority, and (3) discussion of the Mercury Strategy for the Bay-Delta System and Watershed.

Final Workshop Agenda

Monday, September 16 and Tuesday, September 17, 2002
Moss Landing Marine Laboratories, Main Seminar Room
8272 Moss Landing Road, Moss Landing, CA

Monday, September 16

8:00 Registrant Sign In

8:30 Welcome and Introductions. Kenneth Coale, Director, Moss Landing Marine Laboratories

8:40 Goals of the Workshop. Scientific Review Committee

Summary Presentations of Findings from the CALFED Project "An Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed"

9:00 Synthesis of Delta Studies. Gary Gill, Texas A&M University (Galveston, TX), Steve Schwarzbach, USGS (Sacramento, CA), Kenneth Coale and Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, CA), Chris Foe, Central Valley Regional Water Quality Control Board (Sacramento, CA), Darell Slotton, University of California (Davis, CA), Gary Heinz, USGS (Laurel, MD), and Jay Davis, San Francisco Estuary Institute (Oakland, CA)

9:30 Mercury Mass Balance for the Freshwater Sacramento-San Joaquin Bay-Delta Estuary. Chris Foe, Central Valley Regional Water Quality Control Board (Sacramento, CA)

10:00 Sediment-Water Exchange and Estuarine Mixing Fluxes in the San Francisco Bay-Delta Watershed. Gary Gill, Texas A&M University (Galveston, TX)

10:45 Assessment of Methyl and Total Mercury in Delta Sediment. Wes Heim, Kenneth Coale and Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, CA)

11:15 Effects of Wetland Restoration on the Production and Bioaccumulation of Methyl Mercury in the Sacramento San Joaquin Delta, California. Darell Slotton, Shaun Ayres, Tom Suchanek, Ronald Weyland, Anne Liston, Chance MacDonald, Douglas Nelson, and Brenda Johnson, University of California (Davis, CA)

11:45 Mercury in Sport Fish From the Delta Region. Jay Davis and Ben Greenfield, San Francisco Estuary Institute (Richmond, CA), Gary Ichikawa and Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, CA)

1:00 Pilot Transplant Studies with the Introduced Asiatic clam, *Corbicula fluminea*, to Measure Methyl Mercury Accumulation in the Sacramento-San Joaquin Delta Estuary. Chris Foe and Stacy Stanish, Central Valley Regional Water Quality Control Board (Sacramento, CA), Mark Stephenson, Moss Landing Marine Laboratories and California Department of Fish and Game (Moss Landing, CA)

1:30 Laboratory Assessment of the Hazards of Mercury to Reproduction in Aquatic Birds. Gary Heinz, USGS (Laurel, MD)

2:00 Field Assessment of Mercury Exposure in Aquatic Birds in the Bay-Delta Ecosystem. Steve Schwarzbach, USGS (Sacramento, CA) and Terry Adelsbach, USFWS (Sacramento, CA)

2:30 Conceptual Model of Hg in Cache Creek. Charles Alpers, and Joe Domagalski, USGS (Sacramento, CA), Darell Slotton, Thomas Suchanek, and Shaun Ayers , University of California (Davis, CA), Nicolas Bloom, Frontier Geosciences (Seattle, WA), and Ronald Churchill and John Clinkenbeard, California Division of Mines and Geology (Sacramento, CA)

2:35 Mercury and Methylmercury Concentrations and Loads within the Cache Creek Watershed, California, January 2000 through May 2001. Joe Domagalski and Charles Alpers, USGS (Sacramento, CA), Darell Slotton, Thomas Suchanek, and Shaun Ayers, University of California (Davis, CA)

3:20 Mercury Bioaccumulation and Trophic Transfer in the Cache Creek Watershed, California, in Relation to Diverse Aqueous Mercury Exposure Conditions. Darell Slotton, Shaun Ayers, Thomas Suchanek, Ronald Weyand, and Anne Liston, University of California (Davis, CA)

3:50 Mercury Loading and Source Bioavailability from the Upper Cache Creek Mining Districts. Thomas Suchanek, USFWS (Sacramento, CA) and University of California (Davis, CA), Darell Slotton, Douglas Nelson, Shaun Ayers, Chance Asher, Ron Weyand, Anne Liston, and Collin Eagles-Smith, University of California (Davis, CA)

4:20 Solid Phase Mercury Speciation and Incubation Studies in or Related to Minesite Runoff in the Cache Creek Watershed. Nicolas Bloom and Eve Preus, Frontier Geosciences, Inc. (Seattle, WA)

4:50 Assessment of the Feasibility of Remediation of Mercury Mine Sources in the Cache Creek Watershed. Ronald Churchill and John Clinkenbeard, California Division of Mines and Geology (Sacramento, CA)

5:20 Engineering Evaluation and Cost Analysis of Alternatives to Remediate the Sulfur Creek Mercury District, Colusa and Lake Counties, California. Greg Reller, TetraTech (Sacramento, CA)

5:50 Synthesis of Cache Creek Studies. Joe Domagalski and Charles Alpers, USGS (Sacramento, CA), Darell Slotton, Thomas Suchanek and Shaun Ayers , University of California (Davis, CA), Nicolas Bloom, Frontier Geosciences (Seattle, WA), and Ronald Churchill and John Clinkenbeard, California Division of Mines and Geology (Sacramento, CA)

Tuesday, September 17

8:00 Open Discussion of Project Results and Hypotheses from "An Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta Watershed." Moderated by Scientific Review Committee

10:15 Direct Measurement of Microbial Mercury Cycling in Sediments of the San Francisco Bay-Delta. Mark Marvin-DiPasquale and Jennifer Agee, USGS (Menlo Park, CA)

Summary Descriptions of Two Future Mercury Projects to be funded by CALFED

10:45 Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries: An Integrated Mass-Balance Assessment Approach. Kenneth Coale, Moss Landing Marine Laboratories (Moss Landing, CA)

11:20 Evaluation of Mercury Transformations and Trophic Transfer in the San Francisco Bay/Delta: Identifying Critical Processes for the Ecosystem Restoration Program. Mark-Marvin DiPasquale, USGS (Menlo Park, CA)

Discussion of the Mercury Science Strategy for the Bay-Delta System and Watershed

1:00 Mercury in the Environment: Key Findings from Other Ecosystem Studies and their Implications for the Bay-Delta System and Watershed. Cynthia Gilmour, Academy of Natural Sciences, Estuarine Research Center (St. Leonard, MD), and David Krabbenhoft, USGS (Middleton, WI)

2:00 Development of the Mercury Science Strategy: Conceptual Framework, Constraints, and Goals. Jim Wiener, University of Wisconsin-La Crosse (La Crosse, WI)

2:30 Public Input on the Mercury Science Strategy. Open Discussion

5:00 Adjourn

Appendix 2. Agenda for the second mercury workshop, which focused on obtaining public input for development of the Mercury Strategy.

Final Workshop Agenda

Mercury Science Strategy for the Bay-Delta System and Watershed

Tuesday, October 8, and Wednesday, October 9, 2002
Moss Landing Marine Laboratories, 8272 Moss Landing Road
Moss Landing, California

TUESDAY, October 8

7:30 am Registrant Sign In

8:00 am Welcome and Opening Remarks. Sam Luoma, CALFED Science Program

8:10 am Objectives of the Workshop. Jim Wiener, University of Wisconsin-La Crosse, La Crosse, Wisconsin

Session 1: The Bay-Delta Ecosystem–Characteristics Relevant to the Cycling of Mercury and Bioaccumulation of Methylmercury (Moderator: David Krabbenhoft)

8:25 am Hydrodynamics of the Bay-Delta System and Watershed. Jon Burau, US Geological Survey (Sacramento, California)

9:05 am Trophic and Community Ecology. Robin Stewart, US Geological Survey (Menlo Park, California)

9:40 am Geoenvironmental Setting: Natural and Mining-Related Anthropogenic Sources of Mercury. Charles Alpers, US Geological Survey (Sacramento, California)

Session 2: The Bay-Delta Ecosystem–State of our Knowledge of the Cycling, Transformation, Bioaccumulation, and Effects of Mercury (Moderator: Dyan Whyte)

10:30 am Mercury in the Bay-Delta Watersheds. Joseph Domagalski, US Geological Survey (Sacramento, California)

11:30 am Mercury in the Bay-Delta System. Mark Stephenson, Moss Landing Marine Laboratories (Moss Landing, California)

Session 3: Key Findings from other Ecosystem-Level Mercury Investigations–Implications for the Bay-Delta System and Watershed (Moderator: Jim Wiener)

1:30 pm Controls on Mercury Cycling in the Florida Everglades. Cynthia Gilmour, Academy of Natural Sciences, Estuarine Research Center (St. Leonard, Maryland)

2:00 pm Mercury Experiment To Assess Atmospheric Loading in Canada and the United States, the METAALICUS Project. Reed Harris, Tetra Tech Inc. (Oakville, Ontario)

2:30 pm Mercury Investigations in Other Estuarine Systems. Kristofer Rolfhus, University of Wisconsin-La Crosse (La Crosse, Wisconsin)

Session 4: Ecological Restoration of Wetlands in the Bay-Delta System and Watershed (Moderator: Cynthia Gilmour)

3:15 pm An Overview of Planned Restoration Activities. Lauren Hastings, CALFED Ecosystem Restoration Program (Sacramento, California)

4:15 pm Characteristics of Wetlands in the Bay-Delta System and their Relation to the Potential Production and Export of Methylmercury. Group Discussion

5:30 pm Adjourn (Meeting of Breakout-Group Leaders to Follow)

WEDNESDAY, October 9

7:30 am Registrant Sign In

Session 5: Towards a Mercury Science Strategy for the Bay-Delta System and Watershed (Moderator: Chris Foe)

8:00 am Goal, Unifying Themes, and Scope of the Strategy. Jim Wiener, University of Wisconsin-La Crosse

8:30 am Conceptual Framework for the Strategy. David Krabbenhoft, US Geological Survey (Middleton, Wisconsin)

9:30 am Framing Management Questions to Formulate a Science Agenda. Dyan Whyte, CALFED and California Regional Water Quality Control Board (Oakland, California)

Session 6: Identification of Management Questions and Goals concerning Mercury in the Bay-Delta System and Watershed

10:30 am Group Discussions (Topical Breakout Groups)

(1) Mercury Sources, Remediation, and Loadings

(2) Monitoring of Mercury in Biota, Health-Risk Assessment, and Risk Communication

(3) Bioaccumulation and Ecological Risk Assessment

(4) Wetland Restoration and Methylmercury Exposure

Session 7: Identification of Critical Information Gaps concerning Mercury in the Bay-Delta System and Watershed

1:30 pm Group Discussions (same topical breakout groups as in Session 6)

Session 8: Formulation of Goals, Objectives, and Priorities for Mercury Investigations in the Bay-Delta System and Watershed

3:30 pm Group Discussions (same topical breakout groups as in Sessions 6 & 7)

5:15 pm Summary Reports of Breakout-Group Leaders (large conference room)

6:15 pm Next Steps in Development of the Strategy. Jim Wiener, University of Wisconsin-La Crosse

6:30 pm Adjourn

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