Remediation Control Strategies and Cost Data for an Economic Analysis of a Mercury Total Maximum Daily Load in California

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Contents

Notation

AMD: Acid Mine Drainage

ATG: Applied Technology Group

BLM: Bureau of Land Management

BNL: Brookhaven National Laboratory

CBA: Cost-Benefit Analysis

CEQA: California Environmental Quality Act

CEPT: Chemically enhanced primary treatment

CWA: Clean Water Act

DOE: Department of Energy

EPA: Environmental Protection Agency

FRTR: Federal Remediation Technologies Roundtable

FS: Forager Sponge

GDP: Gross Domestic Price

HCAS: Historical Cost Analysis System

JAMA: Journal of American Medical Association

MTSS: Mercury Transportable Stabilization System

NEPA: National Environmental Policy Act

NPDES: National Pollutant Discharge Elimination System

NPL: National Priorities List

NPS: Nonpoint-Source

PCA: Porter-Cologne Water Quality Control Act

PS: Point-Source

PSM: Polar Star Mine

ROD: Record of Decision

RWQCB: Regional Water Quality Control Board

SBMM: Sulphur Bank Mercury Mine

SRCSD: Sacramento Regional County Sanitation District

SWRCB: State Water Resources Control Board

TMDL: Total Maximum Daily Load

TTLC: Total Threshold Limit Concentration

WBS: Work Breakdown Structure

WQO: Water Quality Objectives

WWTP: Wastewater treatment plant

USDA: United States Department of Agriculture

USFS: United States Forest Service

Notation for Tables and Appendices

AC	Acre
BV	Bed Volume
CF	Cubic Foot
CM	Cubic Meter
CY	Cubic Yard
Hg	Mercury
LF	Lineal Foot
LS	Lump Sump
MeHg	Methyl Mercury
MGD	Million gallons per day
N/A	Not available
SF	Square Foot
SY	Square Yard
THg	Total Mercury
TMeHg	Total Methyl Mercury

Abstract

Regional Water Quality Control Board staffs are given the challenging task of developing total maximum daily loads (TMDL) for numerous watersheds. The complexity of mercury fate and transport, speciation, and biological consequences does not make this job easier. Applying cost estimates for mercury remediation projects complicates the situation even further. However, compiling information on past, current, and proposed projects reveals some insights into general categories of types of remediation costs. Numerous mercury technologies, reduction programs, and remediation techniques provide a clearer vision of the types of activities that public or private entities can do to reduce the risk of mercury contamination and the associated costs of these activities. Gold and mercury mine remediation, mercury reduction programs, sediment management, and ecosystem restoration projects are all possible solutions with certain advantages and disadvantages. Agencies have to decide which priorities are more important when assessing a potential remediation project, area, technique, and activity.

This report focuses on the costs that are associated with a suite of PS and NPS remedial strategies that are applicable to mercury sources for use as a resource in developing an economic analysis for mercury TMDLs in California. These costs are for past, current, and proposed remedial projects comprising of project development, environmental compliance, permit approval, cleanup, construction, and other transaction costs. The purpose of the report is to illustrate the general costs associated with various remedial practices that are applicable to mercury sources in California.

Mercury mitigation efforts could focus on two problems that mercury imposes on the natural environment and the general human population. These problems are the accumulation of mercury in the physical environment, given mercury’s affinity for sediment, and the transformation of mercury in response to environmental conditions to an organic form, methyl mercury, which can potentially cause adverse health effects. These problems can be mitigated through mine remediation or sediment control or disposal, as well as through ecosystem restoration projects (although there is the possibility of adverse effects as well).

Although there are several thousand more mines in California, the lengthy and costly endeavor of mitigating mercury contamination prevents many projects from proceeding from the planning stages to the implementation phases. In addition, there are litigation concerns by many mine owners who fear being held liable for future contamination if a site is not fully mitigated. Furthermore, very few projects have been implemented to reduce mercury-laden sediment or to alter ecosystems specifically for mercury reduction. Although costs for remediation projects are site specific, there are some methods for predicting costs through identification and assessment techniques. This report provides an overview of the costs associated with mercury remediation projects in California, along with mitigation strategies in reducing mercury contamination.

I. Introduction

Regional Water Quality Control Board (RWQCB) staff are currently preparing total maximum daily loads (TMDL) for mercury in California. The objective of a mercury TMDL is to lower mercury levels so that the beneficial uses of a water body are fully supported (CVRWQCB, 2001a,b). In California, the Porter-Cologne Act (PCA) requires that economic considerations must be one of the factors considered when establishing a TMDL and mercury control program (PCA §13241, 2003).

The RWQCBs "must consider economics in establishing water-quality objectives[1] that ensure the reasonable protection of beneficial uses" (Vassey, 1999). In addition, the Environmental Protection Agency's (EPA) guidance states that the RWQCB must analyze the costs of methods to achieve compliance with proposed objectives. However, RWQCBs are not required to do a formal cost-benefit analysis (Vassey, 1999). The initial step in this direction of analyzing different technologies for mercury remediation is assessing mercury remedial options and their costs.

Economic considerations include exploring the costs associated with the various remedial practices that are applicable to mercury sources in a water body. This report will outline the general remedial strategies, along with remediation activities and costs associated with each of the remedial alternatives. Various questions, concerns, and issues arise when quantifying remediation costs. Therefore, this report will describe the remediation process and how it affects cost predictions for remediation projects. It will discuss potential remediation control strategies to help make mercury remediation decisions for the future. In addition, detailed information on past, present, and proposed remediation projects involving mercury will be provided.

Information on remediation costs was collected on numerous projects and sites for different years. For comparison purposes, a Gross Domestic Price (GDP) deflator was used to adjust costs from one year to another using a GDP deflator inflation index (***http://www.jsc.nasa.gov/bu2/inflateGDP.html***). All of the costs in the text of this document report 2003 deflator costs. For original cost estimates, please review citations.

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[1] PCA Water Code 13241 (2003). The other factors include the past, present, and probable future beneficial uses of water; environmental characteristics of the hydrographic unit under consideration; water quality conditions that could reasonably be achieved through the coordinated control of all factors affecting water quality in the area.

II. Mercury Remedial Options Summary

The TMDL water quality objectives (WQO) and water quality program will result in impacts on the regulated community, including costs of mitigation measures, as well as time requirements for permits, reports, and administration. Each water quality control program will most likely require a suite of the following point-source (PS) and nonpoint-source (NPS) remedial strategies:

- Gold and mercury mine remediation: stabilizing pit walls, removing sluice boxes, plugging sluice tunnels, backfilling mine pits

- Mercury reduction programs: mercury recycling and collection

- Sediment management: erosion control activities in areas that supply sediment with high mercury levels

- Ecosystem restoration: wetland modification projects

This section of the report provides a summary of the different remediation strategies and general costs. Remedial practices associated with each of these strategies along with their unit costs, “per foot,” “per cubic yard,” or “per acre,” are listed. We note, however, that unit costs do not translate readily to remediation technology costs in general or mine remediation specifically. Remediation unit costs are site specific and must always be considered in terms of how closely the site conditions match the conditions that were present when/where the unit costs were derived. Economies of scale can alter unit costs as well. These costs may comprise the following:

- Project plan development (technical designs and alternatives analysis)

- Determination of environmental effects and compliance with the California Environmental Quality Act (CEQA), National Environmental Policy Act (NEPA), CWA, and other applicable local, State, and Federal environmental regulations
- Acquisition of other nonenvironmental approvals and permits
- Construction, long-term maintenance, and monitoring

(Wood, 2002)

Table 1. Summary of mercury remediation projects/technologies/programs (Wood, 2003)

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Mercury (Hg) Mine Sites in California

Project	Location (County)	Volume	Total Cost ($)	Unit Costs ($)
Buena Vista	San Luis Obispo	474,100 CY	1,349,754–7,758,188	2.85–16.36/CY
Gambonini	Marin	218,000 CY	3.06–3.67 million	14.04–16.84/CY
Polar Star Mine	Placer	500 CY	1.56 million	3,120/CY
Sulphur Bank	Lake	193,600 CY	180,000–69.5 million	0.93–358.99/CY
Gibraltar	Santa Barbara	5,555 CY	282,804–572,997 (without contracting–with contracting costs)	50.91–103.15/CY
Aurora	San Benito	1,630 CY	15,300	9.39/CY
Alpine	San Benito	6,500 CY	127,500–331,500	19.62–51/CY
Carson River	Lyon, Storey, Churchill, (Calif./Nev.)	9,087 CY	3,200,000–3,350,214	352.15–368.68/CY
New Almaden	Santa Clara	2,500 CY	3,996,000	1598.40/CY
Total Unit Costs for Mercury Mine Sites				0.93–15.98/CY

Hg Remediation Techniques, Technologies, and Programs

Type	Description	Area/Volume	Total Cost ($)	Unit Costs ($)
Encapsulation (study)	Acid mine drainage	Amt. of binder depends on acid type, (5–10% cement binder)	N/A	12.90–16.10/ton
Living island (research)	Using plants	N/A	3.37–5.87 million	N/A
Scoop/bury (study)	Interferes with methylation cycle	N/A	35,700–120,360	35,700–120,360
Passivation (study)	Coats tailings to prevent Hg	65 AC	239,654–288,370	0.32–0.54/ton; 3,687–4,436/AC
Soil washing (study)	Ex situ treatment;	25,000–200,000 tons	7,335,000–34,640,000	171.8–293.4/ton
Recycling programs	Collection efforts	220 lb	1,248	5.67/lb
		15 lb	102	6.8/lb
		200–300 lb	10,640–11,064	35.45–55.32/lb
		73 lb	4392.28	60.17/lb
Acid leaching (study)	Changes Hg species	6–8 tons/hr	2,910–17,232	485–2,154/ton

Retorting (study)	Altering transport mechanisms	3–12 tons/day	1,617–25,848	539–2,154

Table 1. Summary of remediation projects/technologies/programs (Wood, 2003)—continued

system				11.88/lb
Sorbents (research tests)	Chemical removal of Hg	10 kg of Hg	8,900–86,430	890–8,643 to remove 1 kg of Hg
Amalgamation using NFS DeHg	Stabilizes elemental Hg	1,500 kg	484,500	323/kg of Hg removed
Polymer filtration technology	Washing and leaching elemental/ionic forms of Hg	Tons	898/yr	21.54–876/ton
Acid rock drainage	Waste rock piles	Ton of waste	Research study	10.87–49.32/ton
	Tailings	Acre of tailings		1,139,288–3,265,803/AC
Total Unit Costs for Hg Controls				0.32–2,154/ton; 2.65–60.17/lb; 323–8,643/ kg of Hg removed
Contaminated Sediment/Erosion Control Activities				
Type	Description	Area/Volme	Total Cost	Unit Costs ($)
Klau Mine: sedimentation basin	Sediment control	150,000 CF	65,466	0.44/CF
Klau Mine: Sediment basin maintenance	Maintaining basin	50 AC	38,189	764/AC
Klau Mine	Seeding and mulching	16 AC	19,203	1,200/AC
Buena Vista Mine	Haul road construction; runoff ditches	8,300 LF	32,024	3.86/LF
Clear lake	Dredging	1,050 AC	57–949 million	54,286–903,806/AC

Table 1. Summary of remediation projects/technologies/programs (Wood, 2003)—continued

	903,806/AC
Ecosystem Modification Projects	

Type	**Description**	**Area/ Volume**	**Total Cost ($)**	**Unit Costs** ($)
Constructed wetlands	Reduce methylation	N/A AC	N/A	50,000–150,000
Suisin Marsh and SF Bay (proposed)	Biological restoration/ monitoring	272 AC	772,667	2,841/AC
Suisan Marsh, Bahia	Land acquisitions	N/A	1,046,000–3,345,000	1,046,000–3,345,000/acquisition
CALFED research studies	Reducing methylation	N/A	300,000–3,881,215	300,000–3,881,215/study
	Monitoring			88,296–136,325
Acid rock drainage	Evaporation	N/A	N/A	2,519–9,329/gal/min
	Passive wetland			3,459–21,671/gal/min
	Lime precipitation			4,124-11,454/gal/min
Total Unit Costs for Ecosystem Modification				2,519–21,671/gal/min; 300,000–3,881,215/study; 2,841–150,000/AC
Wastewater Treatment Plant Hg reduction options				
Sacramento Regional County Sanitation District	Chemically enhanced primary treatment	MGD	N/A	75,250–76,755
	Multimedia filtration			500,120–510,122
	Micro filtration			1,900,450–1,938,459
	Reverse osmosis			877,000–3,571,020
	Ion exchange			900,000
	Brine treatment			146,000
Total Unit Costs for Wastewater Treatment Plant Hg Reduction				75,250–3,571,020 MGD

III. Historical And Future Mining Remediation Projects[2]

This section of the report details some of the remediation projects that have been carried out in California. Reviews of each of these projects include descriptive information (project size and location), project costs, and total and unit costs. Unit costs do not translate readily to remediation technology costs in general. Remediation unit costs are site specific and must always be considered in terms of how closely the site conditions match the conditions that were present when/where the unit costs were derived.

Point sources, regulated under a National Pollutant Discharge Elimination System (NPDES) permit, are initially targeted to reduce pollution from their systems before regulators focus on NPS problems. Although this analysis will focus on NPS remedial strategies, section A will initially concentrate on PS reduction opportunities. Many different local, State, and Federal agencies, in addition to consultants, engineers, geologists, hydrologists, and academic researchers, assisted in developing this economic analysis.

A. Point-Source Reductions

Regulators initially target PSs (that is, wastewater treatment facilities, industrial facilities, and so on) for contaminant reductions, because they are easier to regulate and monitor. This section will briefly give an overview of potential costs for one treatment facility, the Sacramento Regional County Sanitation District (SRCSD). The SRCSD was issued an NPDES Permit in August 2000 requiring the submittal of an offset (pollutant trading) feasibility study and also a treatment feasibility study for mercury (SRCSD, 2001). The SRCSD is still in the early stages of both of these studies; however, various treatment alternatives have been screened. The treatment alternatives, along with preliminary mercury removal efficiencies and project costs, are listed in table 2.

Table 2. Mercury treatment alternatives for SRCSD

(after Carollo, 2002)[3]

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[2] Information on remediation costs was collected on numerous projects and sites for different years. For comparison purposes, a gross domestic price (GDP) deflator was used to adjust costs from one year to another using a GDP deflator inflation index (*http://www.jsc.nasa.gov/bu2/inflateGDP.html*). All of the costs in the text of this document report 2003 deflator costs. For original cost estimates, please review citations.

[3] The estimated unit costs shown are for additional treatment above what is already accomplished at Sacramento Regional Wastewater Treatment Plant. SRWTP currently removes approximately 95% of mercury from the influent. The removal efficiencies cited on this table are, for example, 97% of the 5% that currently remains in the effluent (Vicki Fry, SRCSD, written commun., 2003).

Treatment alternative	Project cost ($/MGD[3]) [4] (price deflator)	O& M cost ($/MG) [5] (price deflator)	Additional sewer service charge ($ESD/month) [6]	Additional sewer connecting charge ($ESD/mon.)	Mercury removal efficiencies
Chemically enhanced primary treatment (CEPT)[1]	75,000 (76,500)	250 (255)	2.50	25	97%
Multimedia filtration	500,000 (510,000)	120 (122)	2.20	150	96%
Microfiltration	1,900,000 (1,938,000)	450 (459)	8.25	570	97%
Reverse osmosis[2]	3,500,000 (3,570,000)	1,000 (1,020)	16.80	1,050	98%

1. CEPT costs are based on retrofit of existing facility.
2. Assumes microfiltration (MF) needed as pretreatment step and includes MF costs.
3. Million gallons per day.
4. Based on averaged day maximum flows conditions, Engineering News Record Construction Costs Index (ENRCCI) of 6,615 and includes engineering, legal, administrative, and CEQA costs.
5. Operation and Maintenance costs are based on average day annual flow (ADAF) conditions
6. 300 GPD per Equivalent Single-Family Dwelling (ESD); capital financing at i=6%, N=20 yr.

In addition, an EPA report, Mercury Study Report to Congress, documents mercury control technologies and costs/financial impact estimates for four different industries: municipal waste combustors, medical waste incinerators, utility boilers, and chlor–alkali plants (EPA, 1997). The report provides information on mercury control strategies, with cost estimates and mercury removal efficiencies.

B. Mercury Mine Sites

Although mercury comes from several sources within the Sacramento Delta and its tributary watersheds, past research and monitoring data indicate that most of the mercury comes from historic mining operation discharges in the Coast Ranges and Sierra Nevada. The following section describes some of these historic mining operations throughout California.

Buena Vista/Klau Mercury Mine Site

The Buena Vista/Klau Mercury Mine, located approximately 12 miles west of Paso Robles, San Luis Obispo County, consists of two parcels of property and 175 acres (Suter, 2001). Mining operations, beginning in the late 1860s and continuing until 1970, contributed mine waste and tailings in drainage channels. Episodic weather events left deep erosional channels throughout the site, thereby releasing mercury-laden sediment, which had impacts on the Las Tablas Creek and the Lake Nacimiento Reservoir (Suter, 2001).

At the Buena Vista Mine site, an engineering evaluation study ($43,084), permitting ($107,710), and engineering design ($53,855) are examples of preliminary administrative activities and costs before any remedial action (SECOR, 1999). In addition, 920 yd^3 were moved to the Klau repository and 7,620 yd^3 were moved to stabilize the slope below the county road. Remediation activities up until May 23, 2001, have an estimated cost of $2,691,152 (Suter, 2001). Final compliance cost estimates are shown in appendix A.

Contact: Gerhardt Hubner (CA RWQCB) (*ghubner@rb3.swrcb.ca.gov*)

Gambonini Mercury Mine

The Gambonini Mercury Mine, located in the steep headwaters region of the Tomales Bay watershed, is approximately 10 miles west of Petaluma, Calif. (Smelser and Whyte, 2002). The Gambonini Mine is a 16-acre mercury mine residing on a geologically unstable site. The development and implementation of an appropriate remediation plan was a long and arduous process. Problem identification, funding negotiations, remediation plan development, and construction required approximately 13 years (with the involvement of four government agencies and a group of engineering geologists).

The Gambonini remediation plan required (1) a highly accurate topographic base map, (2) an analysis of historic aerial photographs, (3) detailed field mapping, and (4) subsurface investigations (Smelser and Whyte, 2002). The objective of this remediation project was to stabilize the primary mine waste deposit and reduce the discharge of mercury-laden sediment, map the distribution of mine waste, and reestimate the volume of primary mine waste deposit. The project required the removal of approximately 218,000 yd^3 of mine waste and weathered bedrock from 5 acres in the upper half of the area (Smesler and Whyte, 2002). In response to 1998’s rainy season and mine discharge of 82 kg of Hg, engineers began a gravity buttress stabilization project costing $1.6 million at a unit cost of $102,290/acre (Lunceford, 2001). Detailed site characterizations were crucial in developing appropriate remediation measures, accurate cost estimates, and efficient project implementation. Table 3 documents the remediation techniques that were assessed as possible remediation alternatives for the Gambonini Mercury Mine (Note: agencies chose to construct the gravity buttress).

Table 3. Remediation alternatives for the Gambonini Mercury Mine (Smelser and Whyte, 2002)

Remediation Technique	Advantages	Disadvantages	Estimated cost
Removing all mine waste from the slope area and placing it in the pit	Mine waste isolated	-Mercury-laden exposure at surface -Minimum of 2 months required to complete investment -Potential high construction costs -Does not stabilize bedrock landslides	$4.59–5.1 million
Stabilizing the waste material in place by building a large retaining wall	Minimal grading	-Mercury-laden mine waste exposed at surface -Minimum of 2 months required to complete investigation and design -Potential high construction costs	$2.96–3.57 million
Stabilizing the waste material in place and using a gravity buttress (**agency choice)	-Simple construction; easier grading	Mercury-laden mine waste exposed at the surface	$3.06–3.67 million

Contact: Dyan Whyte (Calif., RWQCB) (*dcw@rb2.swrcb.ca.gov*).

Polar Star Mine (PSM)

The Polar Star Mine, located near Dutch Flat, Calif., 30 miles northeast of Auburn, Calif., in Placer county, is an abandoned placer gold mine where hydraulic techniques were used to transport water and gravels through tunnels containing a sluice box. The removal action reduced but did not eliminate sources of mercury loading. The amount of reduction is unknown. Specifically, the cleanup approach consisted of the following steps (field work started in May 2000):

- Develop a comprehensive site safety plan for all activities
- Inspect PSM tunnel and implement recommendations regarding tunnel stability, ventilation, and safety
- Contain ground water flowing through the tunnel before start of field work
- Excavate/remove wooden sluice box and boulders from PSM tunnel
- Remove mercury-contaminated gravels and arrange for transportation and disposal of such gravels

(EPA, 2000)

The remediation action by EPA consisted of removing contaminated sediment and the sluice box assembly from the site and sending it to a hazardous waste landfill. The entire length of the tunnel was then lined with concrete to prevent contaminated sediment from reaching the Bear River and to stop small-scale panning at the site. The EPA Emergency Response Unit successfully used the sediment removal technique costing nearly $1.56 million to clean up 500 yd of tunnel/sluice (Lawler, 2001; Lunceford, 2001).

Contact: Rick Humphreys (SWRCB) (*humpr@swrcb.ca.gov*)

Sulphur Bank Mercury Mine Superfund Site (SBMM)

The 120-acre Sulphur Bank Mercury Mine Site, located near Clear Lake Oaks, Calif., was mined for sulfur (1856–71) and mined intermittently by underground methods (1873–1905) and pit mining (1915–57) (EPA, 2002). The mine tailings extend into the Clear Lake Oaks Water District that provides municipal drinking water for 4,700 people (EPA, 2002). The SBMM is currently owned by the Bradley Mining Company, which the EPA has identified as the potentially responsible party (Cooke and Morris, 2002). In addition, Superfund has already obligated approximately $5.1 million for remediation (Tinsley, 2002). On November 1, 1999, contractors hired by the U.S. Army Corps of Engineers, through an EPA contract, constructed surface water diversions on and near the mine site, preventing contaminated sediments and water from flowing into Clear Lake, Herman Pit, and offsite. Other response actions included storm-water controls, soil removal and impoundment, and lake sediment investigations (CVRWQCB, 2001).

The RWQCB's "Amendment to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins for the Control of Mercury in Clear Lake" draft report provides estimated costs of potential remediation activities. Appendix B describes some of the potential remediation actions and costs (Cooke and Morris, 2002).

Contact: Patrick Morris (CA RWQCB) (*MorrisP@rb5s.swrcb.ca.gov*)

Gibraltar Mine and Mill

The Gibraltar Mine and Mill site, an abandoned mining facility since 1991, is located on Federal land under the jurisdiction and control of the U.S. Department of Agriculture Forest Service (DeGraff, 2000). Located within the Santa Barbara Ranger District of the Los Padres National Forest, the site encompasses an area adjacent to the Gibraltar Reservoir within the Santa Ynez River watershed. The main concern of the site was the potential exposure to free mercury within the main mill building (DeGraff, 2000). Mercury contamination was caused at this site through the creation of waste spillage to the milling and mining operation and lack of reclamation. Onsite removal activities began in the early summer of 1999, after a number of environmental and economic assessments were completed (Ecology and Environment, 1999).

During fiscal year 1999, costs included direct costs for removal actions ($36,509) and also for mine reclamation work ($246,295) totaling $282,804 (DeGraff, 2000). Contracts costs to Ecology and the Environment totaled $290,193 (DeGraff, 2000). Costs not included in these figures are those for reconstruction of the access road, addressing the biologic impacts, and oversight time by the onscene coordinator. Removal actions were considered to be effective since the highest concentrations of mercury at the Gibraltar Mine and Mill site were removed from the condenser troughs.

Contact: Jerome Degraff (USFS) (*jdegraff@fs.fed.us*)

New Idria Mine Area (Five abandoned mercury retort sites)

In the larger New Idria mine area, remediation took place at the Aurora and Alpine Mines. Remediation took place at three very small mine sites, approximately 1–5 acres, costing under $15,300. The costs were low because of the simple design of the tailings, and retorts/buildings were buried in a large hole (repository). These small sites were completed within 5 days. Remediation at two larger mines (5–10 acres) was completed in 1–2 months and involved 5,000–8,000 yd^3 of retorted ore. These larger sites cost approximately $127,500–331,500 (Tim Moore, written commun., 2002).

Contact: Tim Moore (BLM) (*Timothy_Moore@ca.blm.gov*).

Carson River Mercury Site (Nevada/California)

Located in Carson, Nevada, in Lyon, Storey, and Churchill Counties, the Carson River Mercury Site is the only site in Nevada listed on the Superfund National Priorities List (NPL). This site includes mercury-contaminated soils at former mill sites and mercury contamination in sediments, fish, and wildlife over more than a 50-mile length of the Carson River.

In 1998–99, the EPA completed a $3.27 million cleanup of mercury-contaminated upland soils at the site. Approximately $3.88 million has been obligated through Superfund's NPL (Tinsley, 2002). The EPA has not attempted or completed any cleanup in the river-reservoir-wetland system. The EPA has been conducting an ecological risk assessment at the site since the early 1990s. A Remedial Investigation and Feasibility Study was conducted in the initial phase in 1993 and its final cleanup plan (Record of Decision (ROD)) was adopted in 1995. The remedy selected in the ROD included excavation of approximately 5,000 yd^3 of contaminated soils exceeding 80 parts per million (ppm) mercury to a maximum depth of 2 feet, backfilling with clean soil, restoration after excavation and backfilling, and offsite disposal of contaminated soil (Ecology and Environment, 2000).

Remedial decisions were based on risk assessments—where there were elevated mercury levels (in soil) and where people were living (toxicity values). The EPA located 100 mills in the area and on the basis of health risks identified 4 mills (areas) that needed to be remediated (all upland areas, including 12 homes). This remediation plan displaced people under the Uniform Relocation Act in which people were compensated with fair market prices for their property. Construction—digging and transporting contaminated soil away from the site (social/environmental costs)—lasted 6 months and cost $3 million. Appendix C illustrates these costs (with 2003 deflator costs) in more detail.

Other notable transaction costs included the following:

- Additional construction costs to excavate and dispose of high Hg soils (additional $742,840)
- Compliance with environmental standards (Historical Preservation Act Requirements) (additional $315,176)

- Change orders—to account for changed field conditions, and so on (additional $275,912)
- Construction delays—increased length of cleanup, thus increasing EPA/E&E oversight costs and onsite field office costs for the remedial subcontractor (additional $31,835-47,754)

(Ecology and Environment, 2000)

Contact: Wayne Praskins (EPA Region IX) (*praskins.wayne@epa.gov*).

C. Proposed Mine Remediation Sites

As more research and site characterizations have been undertaken at various mine sites in response to water quality standards and the TMDL process, more remediation projects within California have been evolving. Detailed site characterizations and preliminary cost figure estimates were done for proposed actions at the following mine sites.

Sailor Flat Hydraulic Mine Site

The Sailor Flat (East) Hydraulic Mine site, located on land administered by the U.S. Forest Service (USFS), (Federal mining claim), approximately 8 miles east of Nevada City, Calif., is a pit 2–3 acres in size created by hydraulic mining techniques, placer mining, logging, and an associated drain tunnel (DeGraff, 2002). Mining activities occurred primarily from the 1850s to 1900, with activities thereafter consisting of small-scale excavations and building improvements. Main features of the site are the mine pit and a 120-foot-long drain tunnel. The former gold mine has both onsite and offsite problems with mercury contamination. Sampling results of water entering and leaving the drain tunnel suggest high levels of mercury contamination in the surface water, in addition to methylation occurrences. Sampling activities and observations have led researchers to conclude that response actions will require mitigating the surface water contamination within the hydraulic pit and discharging from the drain tunnel. In addition, some type of removal of mercury-contaminated wood from sluices will also need to be done (DeGraff, 2002).

The USFS has been selected to conduct a nontime-critical remediation of the Sailor Flat mine site. An engineering evaluation and a cost analysis (EE/CA) for several proposed alternatives were made available for public comment in July 2002. The proposed action is an “excavation and fill” technique (Rick Weaver, oral commun., 2003).

The following proposed actions were evaluated:

1. Excavate and fill: The soil and rock above the tunnel would be excavated by machine to expose the tunnel, then a concrete or polymer synthetic mixture would be pumped into the sluice cut to stabilize and solidify the contaminated sediment. The estimated cost of this alternative is $139,973.

2. Isolate and plug: Mercury-contaminated sediments would be isolated to prevent further methylation in the future. The steps taken in this remediation action are similar to those in the first option. Contaminated sediments would be stabilized with a concrete or polymer synthetic mixture. The vertical inlet to the tunnel would be plugged with an impermeable barrier, and the remaining volume of the inlet would be filled with excavated material. The outlet end would be blocked with a steel gate. Estimated cost of this alternative is $177,738.
(USFS, 2003)

Both alternatives would also involve the treatment of mercury-impregnated wood from old sluices.

The USFS chose the first alternative as most cost effective. The project is still in the design phase, and a new estimate of the total cost is >$500,000 (R. Weaver, oral comm., 2003), which will require additional sources of funding.

Buckeye Diggings Hydraulic Mine

Also located in Nevada City, Calif., the Buckeye Diggings Mine was found to have been releasing hazardous substances to the environment since 1852 (USFS, 2002). Miners constructed deep channels and tunnels to sustain water pressure to conduct the hydraulic mining and recover gold. Mercury was used extensively as part of the gold recovery process. Nearly 20–30 percent of the mercury used in the sluice box was lost to the downstream watershed as part of the gold recovery method (USFS, 2002). The preliminary assessment did not contain cost estimates for mitigation actions.

Guadalupe River Watershed Preliminary Plan

A recent report reviewed possible mercury remediation methods to be used for sites within the Guadalupe River Watershed in San Jose, Calif. (Fuller, 2002). The New Almaden Mine, located in the higher elevation of the Guadalupe River, is the main contributor of mercury to this area.

An estimated 30-year cost estimate for various remediation strategies for a 12 acre polluted site was “$12,000,000 for excavation and disposal, $6,300,000 for soil washing, $600,000 for a soil cap, and $200,000 for phytoextraction” (Fuller, 2002). Additional remediation methods are mentioned in this paper (table 4).

Table 4. Potential remediation methods for the Guadalupe River Watershed after Fuller, 2002)

Method	Description	Cost	Advantages	Disadvantages	Special Requirements
Removal	Dredging and pumping out contaminated materials	$1million /AC	Well-tested and effective	Expensive, lengthy process; disposal sites can leak, release contaminant	Expensive equipment; must be monitored periodically and followed by either treatment and/or burial and containment in other location
Treatments	Physical treatment (sorting)	$500,000 /AC	Good for large quantities of sediment (20-40 tons/hr)	Does not work with high silt, clay content, soil/sediments	These methods often are best applied offsite in contaminated medium that has been removed
	Thermal		Hg compounds are highly volatile at low temperatures	Causes more atmospheric Hg	
	Chemical		Hg can be made biologically unavailable	Adding foreign chemicals into an ecosystem can be dangerous	
Immobilization	Physical barriers placed on site to contain the contaminant	$50,000/ AC	Well-tested and effective	High cost, barriers are of questionable permanence, unknown ecological effects	Barriers can be top, bottom, or lateral side barriers; some can be natural and not manmade
Microbial action	Microbes can demethylate Hg	N/A	Effective in sludges, wastewater, and controlled environments	Not proven for onsite remediation	Forms the basis of phytoremediation
Phytoremediation	Techniques using plants to remove Hg from the environment or immobilizing it within the environment	$16,700 /AC	Cost effective, less intrusive than other methods, pollution captured can be recycled and reused instead of mining more	Plants grow slowly, results take a while, Hg captured in plant may be available to wildlife feeding, not well tested	Best used for sites with low to medium levels of contamination
Water quality management	Manipulates water quality such as oxygen content or pH to prevent MeHg	Cost: varies	Cost effective, less intrusive, and not a highly technical technique	Manipulations need to be monitored; also may disrupt some ecosystem functioning	Most easily implemented by current water managing agencies

Boston Mine Preliminary Remediation Plan

The following is a description of a proposed project at the Boston Mine near Nevada City, Calif. (Lawler, 2001). The Boston Hydraulic Mine is a 40-acre mine site containing significant concentrations of elemental and methyl mercury in sediments located on the floor of a 200-foot sluice box. Several remediation proposals have been suggested by the members of the Bear-Yuba Technical Group for effective cleanup of mercury contamination at the hydraulic mine sluice tunnel and hydraulic mine ponds. The proposed Boston Mine Remediation Project is expected to require 2–3 years for successful completion. Suggested remediation techniques include the following:

- Sediment Removal Method ($156,000)

  Sediments are removed from the floor and sides of the sluice tunnel, initially by mechanized equipment, and subsequently by manual methods. The operation is started at the upstream end of the tunnel so that the tunnel floor is not recontaminated downstream.

- Bat-Gate Installation on tunnel portals ($20,800)

  Mine gates could prevent ongoing access into the tunnel by the general public. Public access into the tunnels can create mercury discharges as the tunnel sediments are disturbed by prospecting activities or by sightseers walking through the tunnel. This method should be regarded as an important first step in the mine tunnel remediation process. This will allow ample time for detailed site characterization and detailed sampling. (Lawler, 2001)

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IV. Mercury Reduction Programs And Techniques

Several techniques exist or are currently being developed for the remediation of mercury and other contaminants. Techniques and technologies include: excavation and treatment (physical separation, thermal treatment, hydrometallurgical treatments), in situ recovery (soil vapour extraction, permeable reactive walls, leaching and extraction, phytoremediation,), and containment (pump-and-treat, stabilization and solidification, sediment capping) (Hinton and Viega, 2001). Mercury reduction programs are also used to reduce this risk. Programs include mercury collection and hazardous waste disposal, restriction of sales of mercury-containing products, reduction of dental waste mercury, and mercury recycling (CVRWQCB, 2001). The following section summarizes the research literature on mercury reduction programs and mercury remediation techniques. Each technique is described, and cost estimates are listed if they are given.

A. Mercury Remediation Techniques and Technologies

The first remediation technology described is an ongoing research project studying the use of encapsulation to treat acid mine drainage (AMD). Dr. Manoranjan Misra, University of Nevada at Reno, has been conducting this research. The cement binder used in encapsulation costs about $12.90–16.10/ton of rock using 5–10 percent by weight cement binder. The amount of binder depends upon the type of acid tailings (Bortolin, 1999).

Living island technologies would remove mercury from water systems through certain plants using solar energy. A small island ecosystem floats atop contaminated water bodies while hydrologic conditions move the water through step-by-step cleanup. Costs are site specific, since size, geology, and mercury concentrations vary. Costs for a proposed 1-year pilot project on Lake Englebright ranged between $3.37 and 5.87 million. However, no such project was ever undertaken (Lunceford, 2001).

Passivation coats tailings with an impermeable coating that prevents mercury from further chemical decomposition. Passivation technology is based on the concept that “reactive rock can be unreactive by covering the reactive rock with a strong and stable coating” (Bortolin, 1999). Onsite equipment eliminates the need to export contaminated material or pay for recycling costs. Costs of passivation for a 65-acre site excavated to 1 foot in depth range between $239,654 and $288,370, or 32–54 cents a ton (Bortolin, 1999).

Soil Washing is an *ex situ* soil remediation technique combining aqueous removal and contaminant separation to lower the remaining contaminant concentration in treated soil to specified levels. Soil washing includes physical separation techniques and extraction techniques, such as chemical leaching and attrition scrubbing. The EPA’s National Risk Management Research Laboratory wrote a report entitled “Contaminants and Remedial Options at Selected Metal-Contaminated Sites” that documents soil-washing costs (table 5).

Table 5. Soil washing unit costs (after EPA, 1995)

	Volume (short tons)			
Cost item	**25,000**	**50,000**	**100,000**	**200,000**
Depreciation	45.8	43.4	17.2	13.7
Mobilization and demobilization	9.2	4.6	3.4	1.1
“Normal” site preparation	13.7	6.9	4.6	2.3
Materials handling	17.2	18.3	17.2	17.2
Labor	34.4	28.6	22.9	17.2
Chemicals	17.2	17.2	17.2	17.2
Maintenance	9.2	6.9	4.6	2.3
Safety equipment	3.4	3.4	3.4	3.4
Utilities	9.2	9.2	9.2	9.2
Process treating	17.2	13.7	9.2	5.7
Disposal of residues	36.7	36.7	36.7	36.7
Management, overhead, profit	80.2	68.8	55.8	45.8
Net price ($/short ton)	293.4	237.9	201.4	171.8

Mercury Transportable Stabilization System

The Mercury Transportable Stabilization System (MTSS), tested by Applied Technology Group (ATG), treats contaminated water. Operating costs are approximately $102/hr (costs include two laborers, health and safety oversight, and management support) (U.S. DOE, 1999). Reagent and material costs, based on the nature of the waste, are expected to range from $54/ton for a dry, easily stabilized waste to $969/ton for a mostly liquid waste (U.S. DOE, 1999). The life-cycle unit cost is estimated to be $1.86/kg at a steady state 1,200 lb per hour processing rate which increases to $3.96/kg when processing at the lower end of the rate range (100 lb/hour) (U.S. DOE, 1999). At Portmouth’s DOE facility in Ohio, ATG tested the application of stabilization of low-level mercury in radioactive wastes. Projected costs for a 1,200 lb/hour stabilization system included capital costs of $31,836 and operating costs of $101/hour. Unit costs were projected at $1.84/kg (FRTR, 2000). However, the actual costs will vary depending upon the type and homogeneity of the waste, the nature of the matrix being processed, and the presence of other hazardous constituents (U.S. DOE, 1999)

Sorbents

Numerous sorbents have been developed for the removal of mercury and heavy metals from watersheds. The following sorbents were tested to remove mercury from microgram-per-liter levels to low nanogram-per-liter levels (Bostick and Klasson, 1998). Table 6 summarizes various sorbents and their costs.

Table 6. Types and costs of various mercury-reducing sorbents (Bostick and Klasson, 1998)

Sorbent type	**Description**	**Recommended conditions**	**Cost ($)**
Ionac SR–3	Binds ionic Hg, MeHg, and elemental Hg	Performs best at pH values between 0 and 6	12/liter
Ionac SR–4	Weakly acidic resin	pH values ranging from 1 to 14; flow rate of 0.3 BV/min	14/liter
Keyle–X	Sulfur-based functional groups; Hg-specific resin	Operates at high flow rates; pre-treat with chlorine to 1–2 mg/l	126/liter
Mersorb L, 3, 1.5 mm	Commercial carbons impregnated with sulfur	Sorption dependent on precipitation of the sulfide	5/liter
Forager sponge	Description below	Pretreated with acid or base	5/liter

The forager sponge (FS), an *in situ* technique for mercury removal, was developed by Dr. Norman Rainer, of Dynaphore, Inc. When fully saturated with mercury, the FS is usually sent to an incineration facility for destruction of the sponge and recovery of the mercury. The FS is composed of little "sponge" cubes that clean up polluted water by absorbing the trace toxic organic and inorganic pollutants in it (Dynaphore, 2002). It is a very effective system that will remove most trace contaminants and can be used anywhere there is polluted water. Table 7 compares the actual use cost of the forager sponge with its most common competitors: beaded ion exchange resin and sulfur-treated activated carbon. In this example, calculations were based on using FS Type M-TU to remove mercury at a 0.2 ppb level (NCER, 2001).

Table 7. Forager sponge compared with other treatments (Dynaphore, 2002)

Absorbent	Forager	Ion exchange	Activated carbon
Material cost	$20/kg	$42/kg	$1.78/kg
Hg loading @ 0.2 ppb	35 g/kg	6.5 g/kg	0.75 g/kg
Quantity needed to remove 1 kg of Hg	29 kg	154 kg	1,333 kg
Waste disposal costs per kg Hg @ $60/cu ft	$310	$489	$6,270
Cost to remove 1 kg	$890	$6,960	$8,643

Amalgamation of Mercury-Contaminated Waste Using NFS DeHg Process

ATG also tested the application of amalgamation of elemental mercury (test locations were in Idaho and Tennessee). This process stabilizes elemental mercury and uses a proprietary reagent to break mercury complexes, and filtrate is either recycled to the reactor or discharged. Assuming the waste is elemental mercury, projected costs for treating more than 1,500 kg were $323/kg, which does not include disposal costs of the treated wastes (FRTR, 2000). Results showed that the process reduced the concentration of mercury to 0.05 mg/L on average (FRTR, 2000). The Colorado Minerals Research Institute performed a similar test, amalgamation of mercury-contaminated waste, and came to the same cost conclusion (U.S. DOE, 1999). This process reduced the free mercury by 99.87 percent to 99.98 percent (FRTR, 2000).

Polymer Filtration Technology for Removal and Stabilization of Mercury

The Los Alamos National Laboratory developed a process for washing and leaching elemental and ionic forms of mercury from solid debris for both high and low concentrations (>260 ppm and <260 ppm, respectively)" (Smith, 2002). The process includes using a leaching solution and multiple ultra filtration applications. Costs depend on the weight of the debris. During this treatability study, throughput could be 2.5 tons/yr of light debris or 50 tons/yr of heavy debris (Smith, 2002). Costs in this study included equipment costs ($40,800), energy costs ($0.055/kWh), or about $898/yr, ranging from $412.90/ton for light debris to $21.54/ton for heavy debris. Chemical costs using reagents from Fisher Scientific or Aldrich Chemical would cost $876/ton for light debris and $318/ton for heavy debris with no polymer regeneration (Smith, 2002). Additional cost estimates for projected cleanups are also mentioned in the report.

Sulfate Reducers

L. Michael Saunders, Georgia Tech University, has been involved in research focusing on the role of sulfate-reducing bacteria (SRB) in the production of Methyl-Hg in marine systems. Saunders explains that in an ideal system, we would want to shut sulfate reducers down, but they are the dominant microbes. In addition, it is the natural cycling of carbon in water systems that dictates their presence in the system and the methylation processes they propagate on uncontaminated sediments (that is, natural soils that contain Hg), as well as contaminated ones (L. Michael Saunders, written commun., 2003). His research includes modeling these processes to predict the impacts of a microbial community on methyl-Hg production and impacts. Given the high level of carbon input through natural processes, these methylation processes are very difficult to stop or attenuate in marine systems (L. Michael Saunders, written commun., 2003).

B. Mercury Recycling Programs

In recycling programs, mercury is recovered and collected by participants, primarily recreational and commercial gold dredgers, in the field and sold to commercial recycling operations at market value. Recycling rarely involves the direct removal of mercury from the watershed. On the other hand, it does prevent mercury from entering the watershed by collecting mercury that might be used in mining activities (by recreational miners) or that might be disposed of improperly. There have been several different recycling programs. The first collection effort in the Nevada County region in 2000 cost $1,248 and gathered 220 lb of mercury from people's garages. Tracy Gidel (Nevada County Environmental Health) said that Nevada County spent nearly $102 to recycle the last 15 lb they collected in 2001. A total of 315 lb has been collected during the 2-year program (Lunceford, 2001). In 2001, Rick Weaver, USFS, collected mercury from people's garages and shipped it to a recycling center. The flasks cost $260 each, and removal costs were $126 (Bethlehem Apparatus Company, Inc.). Table 8 provides an example of recycling costs.

Table 8. Recycling costs (Lunceford, 2001)

	Shipping and handling costs	**2003 costs**
West Sacramento	200–300 lbs	$362–$786
	Flasks ($260 X 2)	$520
	Processing	$126
	Total:	$1,008–1,432
Total recycling costs for 2003		
Agency labor	(Reduced from 2000 figures by 45% + 5 hours County Personnel + truck rental	$9,010
Contractor costs		$102
Container acquisition		$520
Shipping and handling		$1,008–1,432
	Total recycling costs	**$10,640–11,064**

Rick Humphreys (SWRCB) summarizes the efforts of the Sacramento River watershed recycling efforts. The program targeted recreational gold miners as a source of potential Hg, but little Hg was recovered from this group. Most of the mercury recovered came from past mining activities (Hg purchased for use in mining and then never used) and had been stored for a long time in peoples' homes (Rick Humpreys, oral commun., 2003). Other sources included laboratories and dental offices. The program had the best success with older people (65+ yrs old) or their heirs. Two individuals contributed 250 lb of mercury, but most people contributed less than 1 lb. Humphreys estimated it cost agencies $16,272 in labor to set up the recycling program in the Sacramento River watershed (Lunceford, 2001).

Palo Alto

Palo Alto’s mercury collection program has been successful in mercury-containing items, including thermometers, thermostats, and fluorescent lamps. As of December 31, 2002, the program had collected nearly 73 lb of mercury, including 1,784 thermometers, 44 thermostats, and 4,310 fluorescent lamps (Weiss, 2003).

Table 9. Fluorescent lamp recycling costs (Weiss, 2003)

Total lights collected	4,310
Total lamp recycling costs	$1520.14
Total shipping/startup costs	$676.00
Total program operation costs	$2196.14
Average cost per light to recycle	$0.51

U.S. Army Environmental Center

Recycling costs for fluorescent lamps are often measured on a linear-foot basis. The average cost is $0.10/linear foot. Costs to recycle high-density lamps range from $1.25 to 4.50, with an average cost of $2.50 (U.S. Army Environmental Center, 1997).

NY–NJ Port Authority/La Guardia Airport

The NY–NJ Port Authority/La Guardia Airport did a cost-benefit analysis (CBA) of recycling vs. disposal of mercury and found that they saved ~$5,000 in 2 years by recycling rather than disposing of mercury (NYC Wasteless, 2001). Recycling costs include a recycling drum costing $23 each and actual recycling costing $64/drum. Disposal costs include $43 for the drum and $1,100/drum for the disposal (disposal drum holds about 7–8 times as many lamps).

C. Mercury Reduction Programs and Studies

Brookhaven National Laboratory Study

Various mercury treatment technologies were reviewed to determine the most viable alternative to treat mercury-contaminated soil at Brookhaven National Laboratory (BNL) (Boyce and others, 1999). BNL is a 5, 265-acre site located in central eastern Long Island, N.Y. The facility is a federally funded international research and learning center managed by Brookhaven Science Associates.

The site has been on EPA’s NPL since December 21, 1989. Technologies that were reviewed include acid leaching, amalgamation, soil washing, retorting, and stabilization (Table 10). Alternatives were based on cost, treatment efficiency, availability, process operating parameters, and the potential for the generation of secondary waste streams. The contaminated material is classified as regulated hazardous waste low mercury (that is, total mercury concentration <260 mg/kg (ppm). The soil is required to become nonhazardous (mercury concentration reduced to <0.2 mg/l) before final disposal (Boyce and others, 1999). According to the RWQCB, the total threshold limit concentration (TTLC) for mercury is 20 mg/kg (ppm) and the soluble TLC is 0.2 mg/l. Mercury concentrations above these levels are considered hazardous (Michelle Wood, CVRWQCB, written commun., 2003).

Table 10. Treatment alternatives from Brookhaven National Laboratory Study (Boyce and others, 1999)

Technology	Process rate	Treatment efficiency	Process duration	Onsite or offsite	Unit cost ($/ton)
Acid leaching	6–8 tons/hr	< 0.2 mg/l	1 hr	Off	485–2,154
Amalgamation	100 lbs/day	< 0.2 mg/l	4 hrs	Off	N/A
Soil washing	200 tons/day	< 0.2 mg/l	N/A	On & Off	162
Retorting	3–12 tons/day	< 0.2 mg/l	4–6 hrs	On & Off	539–2,154
Stabilization	40 tons/day	< 0.2 mg/l	N/A	On & Off	43–2,154

Conclusions from this study include the following:

- Stabilization was found to be the most preferred alternative because of the relatively low cost, the treatment efficiency, and low likelihood for the production of significant secondary waste streams.
- Soil–washing ranked high because of its low cost and high processing rate; however, it most likely requires a secondary treatment for the condensed mercury waste volume.
- Retorting is not recommended as the best treatment alternative because of its high cost and the possibility of having to amalgamate the recovered mercury.
- Acid leaching is not preferred because of the potentially large secondary waste streams, high cost, and availability.

(Boyce and others, 1999)

Dental Programs

Dentists are the third largest users of mercury in the United States. In 2001, dentists used 40 metric tons of mercury (20 percent of the total amount used in that year), most of which was released to the environment (Bender, 2002). It is relatively inexpensive (<$50/month) for dentists to remove and recycle mercury from their offices (Bender, 2002). The Bender (2002) report recommends (in part) the following steps:

1. The release of dental amalgam into waste streams should be prohibited. All mercury should be trapped, collected, and recycled.
2. This should be fostered through voluntary incentives, technical assistance, and mandates to encourage and/or require dentists to follow best management practices, install amalgam separators, clean and replace mercury-contaminated pipes and plumbing, manage excess mercury, and submit annual reports on their reduction initiatives.
3. The dental amalgam separators can reduce mercury discharge by 95 percent or more.

Bender (on the basis of references in the report) further reports that coarse, chair- side traps can collect ~60 percent of all amalgam waste, and 95 percent or more can be captured when an amalgam separator is added to the system. The cost of operating an amalgam separator ranges from $47.95 to

$100/month (Bender, 2002). The following table (table 11) illustrates mercury remediation technologies used by dentists and their costs, taken from a report documented specifically for the State of Minnesota.

Table 11. Estimated effectiveness of amalgamation activities (Minnesota Pollution Control Agency, 2000)

Recycling activity	Mass of recycled Hg	Estimated captured pounds of Hg in Minn.	Estimated cost per dentist ($)	Estimated cost per pound of Hg removed ($)
Chair-side traps	0.6–1.2	586–1172	6.4–12.7	26.5
Vacuum-pump traps	0.25–0.50	258–516	19.1–37.1	371–743
Wastewater settable particles	0.05–0.25	52–258	53–159	478–72,374
Wastewater soluble particles	0.005	5.2	1,592	723,739

Table 10 demonstrates the potential escalating cost impact to dentistry and the dental public at each higher level of amalgamation waste removal. Equipment costs vary as well. Options for low-cost systems range from a simple sedimentation tank produced for as little as $53–318 to high-end equipment, such as centrifuges, costing as much as $3,184. Among commercial vendors, one complete capture system is marketed for an installed cost of $2,011, with an annual service fee of $345–403. A service claiming the capability to provide below-detection discharge (200 parts per trillion) that includes full service waste management is currently marketed for about $1,592 per year.

Manufacturers' claims of 90–99 percent removal rates remain largely unsubstantiated by published data, thus making accurate cost-effectiveness comparisons impossible (Minnesota Pollution Control Agency, 2000). The agency report suggests that before acceptance of any systems for general use evaluation procedures should be performed to assess effectiveness, efficiency, practicality, dependability, and final destination of removed wastes, as well as relative costs.

EIP Associates Study

EIP performed a qualitative cost-effectiveness analysis of several potential mercury reduction programs (Johnson, 2000). In the analysis, the cost-effectiveness of each program was determined by evaluating the potential quantity of mercury removed versus the potential cost of the program. They report that the best opportunities for cost-effective mercury reduction programs might focus on education/outreach for dental offices, voluntary audits at dental offices, and bans on mercury thermometer sales.

Other cost-effective opportunities for mercury reduction are as follows:

- Education/outreach for hospitals, medical offices, laboratories, and the general public
- Voluntary audits at hospitals and medical offices
- Plumbing/trap cleaning at hospitals, medical offices, dental offices, laboratories, and educational institutions
- Bulk mercury collection for dental offices and for the general public
- Installation of amalgam separators at dental offices

- Mercury thermometer take-back
- Legislative lobbying and lobbying of professional organizations
- Fluorescent bulb collection
- Promotion of city policies to reduce mercury

Ross and Associates Report

In the draft report on mercury reduction options, various options are evaluated for their cost effectiveness as measured in dollars/lb. Among the lower cost strategies, the most cost effective appears to be the collection of raw mercury ($10/lb), reducing Hg use in consumer products ($10-100/lb), and the purchase and use of lower Hg containing products ($10-100/lb). Among the medium cost options, laboratory pollution prevention ($700-6,600/lb), enhanced air pollution control ($3,400-7,600/lb), and scrubber water treatment ($2,000-20,000/lb) were deemed most cost effective. For the higher cost options, carbon injection at 60 percent overall Hg collection efficiency ($11,000-300,000/lb), lower exhaust temperature ($100,000-125,000/lb), and carbon injection at 30 percent overall Hg collection efficiency ($37,000-200,000/lb) are most cost effective. The least cost effective option (by far) is to use the best available control technology to capture Hg in WWTP water discharge ($5,500,000/lb). The report concludes that laboratory pollution prevention offers the greatest reduction potential (20,394 lb/yr) (Ross and Associates, 2000).

D. Sediment Control and Disposal

Reductions in the total amount of mercury-laden sediment will increase the chance of reducing the total amount of mercury available for bioaccumulation. Various measures of erosion control and sediment management options provide another remedial possibility to either prevent contaminated sediment from reaching watersheds or remove existing contaminated sediments. These sediment management options include the following:

1. *Stream channel dredging*: removal and disposal of instream sediments and associated mercury from historical hydraulic mining activity
2. *Reservoir dredging*: removal and disposal of sediments and associated mercury deposited in study area reservoirs
3. *Reservoir operational changes*: modifying the operation of major reservoirs to maximize the deposition of sediment and associated mercury from the water column

(Weiner and others, 2003)

The EPA prepared a report by the Engineering and Technology Work Group as part of the Assessment and Remediation of Contaminated Sediments Program illustrating some of the costs of treating and disposing of contaminated sediments. These contaminated sediments are not necessarily contaminated with mercury but can be used as a reference for similar projects. This report gives additional unit-cost figures for various transport mediums of selected dredged material volumes (EPA, 1994). Furthermore, this report documents unit costs for disposal technologies and gives information on references for cost data (Table 12).

Table 12. Sources of information for cost data

(EPA, 1994)

Source	Type of information
R.S. means cost data	Unit costs for various construction activities
Dodge guide	Unit costs for various construction activities
Corps unit price books	Unit costs for various construction activities
Marshall Stevens Index	Treatment plant and equipment costs and index
Chemical engineering	Treatment plant and equipment costs
Engineering news record	Construction cost index for updating capital costs
Civil works construction cost index system	Regional adjustment factors for construction costs
U.S. Dept. of Energy	Energy costs, regional differences
U.S. Dept. of Labor	Labor costs, regional differences
Federal Emergency Admin.	Relocation costs

E. Ecosystem Restoration

Mercury remediation projects can also target those variables that reduce health risks caused by mercury contamination. Methyl mercury is a highly toxic form that readily accumulates in exposed organisms and biomagnifies to higher concentrations in commercial fish, causing adverse health effects when consumed by humans (Weiner and others, 2003).

The physical and chemical factors contributing to the production and breakdown of methyl mercury should be the focus of ecosystem restoration activities. Wetland restoration, restoration of seasonal floodplains, channel reconstruction, and dam removal are examples of restoration activities considered most likely to affect mercury cycling and methyl mercury exposure (Weiner and others, 2003). However, the relative influence of many of the variables (for instance, habitat type, temperature, water chemistry, and so on) on the production and bioaccumulation of methyl mercury remains poorly quantified. Wetlands and other ecosystem projects have the potential to both help and hinder water quality problems. Therefore, very few restoration projects have been undertaken solely to reduce methylation.

The following section briefly explores remediation and research activities regarding ecosystem modifications and mercury. Although there are very few restoration projects and technologies specifically pertaining to mercury remediation, the following information presents an overview of restoration dealing with metals. The RWQCB staff and other agencies will explore this effort much further in the future.

Wetland/Marsh Research Projects and Technologies

The Savannah River site, based in South Carolina, designed and built a constructed wetland to treat a particular waste stream for copper and its subsequent toxicity (Sarah Harmon, written commun., 2002). After construction of the wetland was completed, it was discovered that the waste stream might also be in violation of mercury limits. A series of pilot-scale studies on the issue of mercury behavior were conducted in this constructed wetland environment. Very low levels of mercury (ppb levels) were found in this case. The pilot wetlands, on average, decreased total mercury concentrations in the outfall stream by 50 percent (King and others, 2001). Mercury efficiency has improved with maturation of the treatment cells within the wetland (Nelson and others, 2002). Since the vegetation has matured, researchers have seen 80 percent removal levels of mercury coming into the wetland system (Eric Nelson, written commun., 2003).

Transformation of mercury to methyl mercury was also observed in the wetland treatment system, showing a seasonal trend and being negligible during the summer months (generally less than 1 ng/L in the effluent). The facility was built for less than $5 million, but costs are very difficult to specify because this is a U.S. Federal facility and is hard to relate to the commercial world. In addition, construction, operation, and maintenance costs are minimal since the system is entirely passive and only requires periodic observation (Nelson, written commun., 2003). Constructed wetland technologies represent a feasible cost-effective means of removing low levels of mercury compared with more expensive treatment options, such as ion exchange (King and others, 2001).

Another research project based in the Savannah River area studied the mercury geochemistry in wetlands and its implications for *in situ* remediation. Results indicated that in ecologically sensitive wetlands, traditional intrusive engineering approaches are not viable remediation options (Kaplan and others, 2002). If mercury is too strongly bound to sediments to permit plants to mine it out of the ground, then phytoremediation is not the best option. In addition, if mercury was not concentrated in the smaller particles, soil washing would be very intrusive and not very effective. If either of these conditions occurs, the best option would be monitored natural attenuation (Kaplan and others, 2002). This approach consists of monitoring for mercury movement in the aqueous phase.

Researchers funded by the EPA Hazardous Substance Research Center examined the roles of certain microbe populations in mercury methylation processes in the bioremediation of contaminated sediments in salt–marsh systems. An assay tool and model to predict the impacts of a microbial community on methyl-Hg production has been developed (L. Michael Saunders, written commun., 2003). These processes are difficult to stop or attenuate in marine systems with high levels of carbon input through natural processes (L. Michael Saunders, written commun., 2003).

An additional project has been evaluating the availability of Hg, methyl Hg, and selenium (Se) +4 and +5 in sediment from a lagoon that is proposed for use in a wetland- creation project (Jack Word, written commun., 2003). The biological tests that were performed include toxicity testing with sediment and sediment elutriates (total Hg and methyl Hg and total Se and +4 and +5 in each media), bioaccumulation into the tissues of invertebrates, and body burdens in plants at the proposed mitigation site and from tissue of lagoon plants where the sediment was obtained. Results showed that even in the presence of much higher total Hg values, the lagoon sediment showed less methyl Hg, and the Hg that was present was not bioaccumulated into tissues of the test organisms. These chemicals were less mobile because the sediment from the lagoon was anaerobic when collected, therefore allowing high levels of total sulfides in the sediment to prevent Hg and Se from settling into the water column or test organisms (Jack Word, written commun., 2003).

Vic McFarland and others are researching the feasibility of using the Hamilton Army Airfield Wetlands restoration site on San Pablo Bay as a case study for developing methods of mitigating methyl mercury production and mobilization in wetlands construction using dredged sediments (McFarland and others, 2002). Thus far, they have monitored total Hg and MeHg during a dry and a wet season at 60 sample sites surrounding this research area site. The dry season work is completed, and the wet season analyses of the same sites are being completed (Vic McFarland, written commun., 2003). The third phase involves intensive geochemical, microbial, plant, and invertebrate analyses and will test sediment amendments for reducing mercury methylation relative to demethylation rates and the effects of plant/microbial communities on mercury methylation (Vic McFarland, written commun., 2003). Cost estimates for wetland monitoring and restoration are provided in appendix D.

In general, constructed wetlands usually cost approximately $100,000 per acre, varying by $50,000 over or under that estimate depending on different physical, hydrological, and chemical characteristics of each site (Matt Huddleston, ENTRIX, written commun., 2003). If existing clays can be compacted sufficiently to protect ground water (assuming this is a treatment wetland), then significant cost savings may be made. Huddleston also claims that the cost of constructing a wetland for mercury treatment would not be significantly greater than constructing one for copper or zinc. The crucial step is to understand the biogeochemical characteristics of a site and then design accordingly.
Finally, in the mid-1990s, the RWQCB (Region 2) did sample mercury concentrations in Suisun Bay and sloughs. No remediation at this site has taken place. However, remediation has taken place at the Stege Marsh that includes the Zeneca site and the UC Richmond field station in Richmond (Karen Taberski, written communication., 2003).

CALFED Research Efforts

In 1994, State and Federal agencies formed the CALFED Bay-Delta program to respond to the growing number of environmental, water quality, and water supply problems in the San Francisco Bay/Sacramento-San Joaquin Delta. As of 2001, more than $250 million of CALFED funds had been spent on 170 ecosystem restoration projects that were underway or completed (CALFED, 2002). These projects focus on wetland restoration, the evaluation of heavy metals (including mercury) in water and fish, habitat protection, and the control of invasive species.[4]

As part of CALFED's strategy for studying mercury and its implications, the CALFED Bay-Delta Agency granted funds in 1998 to the University of California at Davis to study the effects of wetland restoration on the production and bioaccumulation of methyl mercury in the Sacramento-San Joaquin Delta watershed. This type of research is driven by the concern that significant new wetland creation in the delta may increase MeHg production, resulting in increased MeHg bioaccumulation in aquatic organisms, as well as in their consumers. Methyl mercury/total mercury ratios and sediment methyl mercury concentrations were found to be "significantly greater in flooded tracts characterized by dense submergent aquatic vegetation, as compared with adjacent Delta channel, mudflat, or sand flat environments" (Slotton and others, 2002).

Heavily vegetated wetland tracts are areas of high total mercury, enhanced methylation, and exporters of elevated MeHg concentrations associated with reduced loads of particulates, yet they vary with season, tract habitat, food web characteristics, and other factors. Additional information on wetland projects throughout the San Francisco Bay Area can be accessed through a map-based database: *www.wetlandtracker.org*.

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[4] http://calfed.water.ca.gov/ProgramTracking_2003/adobe_pdf/ERPProgramTracking_Jan2003.pdf for a list of active projects

V. Disclaimers On Remediation Cost Predictions

Remediation cost figures for modern mines, as well as other remediation activities, are not well documented in the public record for several reasons. These reasons may include the following:

- Specific remedial actions taken must be reported to regulator agencies, but costs typically are not.
- Some actions may be short-term measures while others are often complex, long–term solutions; therefore, cumulative cost data are not usually gathered correctly.
- Costs are often considered proprietary to the mine operator.

(EPA, 1997)

Therefore, forecasting costs for future mitigation decisions on the basis of past projects and remedial actions may be poor at best. There are some significant issues to consider in predicting unit costs for future remediation projects using these past figures from previous sites, mercury reduction programs, and technologies. Experts from the geology and engineering fields describe some of the issues in making predictions for cost estimates for future sites on the basis of past projects.

Ron Churchill (California Department of Conservation, Division of Mines and Geology), a geologist, explains some of these issues. According to Churchill, mine remediation is site specific, and there is no such thing as an average mercury or gold mine. California alone contains more than 600 mercury mines and prospects and more than 14,000 gold mines. On this subject he writes:

- Very similar mines with regard to mine size, history, and deposit type may require dramatically different reclamation activities because of geographic setting, and others will require no reclamation at all.
- Some mercury and gold mines contain AMD problems, and others don't.
- Attempting to recover mercury from a site where it is an issue isn't always the best approach. Isolation and containment on or near the mine site makes more sense from the scientific/engineering standpoint and monetarily.
- Not all elevated mercury at a mercury mine site is present in waste rock piles, tailings piles, ore piles, or processing facilities, but mercury is elevated in local soil and rock at the mine site by entirely natural processes.

(Ron Churchill, written commun., 2002)

Greg Reller (Tetra Tech), an engineer, has had experience with mercury remediation projects and identifying unit costs. Greg comments:

> Mine costs do not translate readily to remediation technology costs in general or mine remediation technology specifically. To estimate remediation costs, engineers and scientists identify a technology (using experience, literature review, and input from others) then critically evaluate how it would work at the specific site of interest. After identifying the technology and figuring out how it would actually be applied to the site, they conceptually break down the technology into components (for example, design, mobilization, staging, preparation, construction, and restoration) and estimate the costs for each component. After a specific technology has been applied to several different sites, unit costs can be derived; however, these

> costs always must be considered in terms of how closely the site conditions match the conditions that were present when/where the unit costs were derived.
>
> For example, let’s say we want to move 10,000 yd^3 of soil and rock to a repository and cap it. In one location and for one set of chemicals, the cost may be on the order of $25/yd^3. At another location and for the same set of chemical conditions, the cost could be $50/yd^3 or more. Variables other than material characteristics (which are very significant) affect costs. Some of these variables include regulations applicable to the project, location, site access, and infrastructure. For these reasons, it may be difficult to try and compare costs directly on the basis of factors such as chemicals present, site geology, and so on.
>
> (Greg Reller, written commun., 2002).

Reller also describes how remediation techniques do not necessarily work for all types of metals:

> - Remediation can be very specific to both metal present and each site. If acid drainage is the issue, then neutralization (say by adding lime in a contact tank) is effective for most metals. However, the contact time required to attain water quality standards will vary by metal.
> - Techniques that are great at one site for a metal may fail at another site with the same metal.
> - Varying chemical characteristics of metals dictate remediation decisions. Consideration of solubility curves for various metals (say solubility with pH) provide a partial answer to this question.
>
> (Greg Reller, written commun., 2002).

Forecasting predictions of future unit costs and total costs for mercury remediation practices can be estimated on the basis of past mercury projects and well understood engineering practices and techniques. However, Reller says that an ‘outcome prediction is usually subjective and based on the degree to which the site is understood and a reputable prediction would never claim absolute certainty. However, using prior experience and the degree to which our data lead to an understanding of the site, we can identify expected outcomes. Measurement of outcomes is usually attained through direct monitoring’ (Reller, 2002).

VI. Remediation Process

Detailed geologic site characterizations are required to provide appropriate remediation measures, accurate cost estimates, and efficient project implementation. The remediation of abandoned mine sites requires much more time than typical geotechnical projects, such as time for identifying and quantifying the mine-related environmental problem, developing mitigation alternatives, undertaking legal action, securing funding, and implementing remediation measures.

A. Factors Affecting Remediation Decisions

Numerous elements are used to evaluate the suitability of specific remedial measures for a given site. The ability to predict contaminant mobility and subsequently make mitigation decisions is based on understanding the distribution and properties of soils, rock types, and site hydrogeology and hydrology in conjunction with physiochemical properties of the contaminant (Hinton and Viega, 2001). Such factors can contribute to a preliminary assessment of risk to human health and provide a basis for evaluating and then designing measures for remediation.

Although numerical criteria developed by government officials are valuable indicators of the occurrence and extent of contamination, sometimes these levels are not economically or technically attainable. More aggressive and costly measures may be warranted if Hg is detected in biota or if the risk of its subsequent incorporation into organisms is bioaccumulative, especially in localized areas. Responses may include the implementation of consumption advisories, educational programs, and technology modifications to lessen exposure to Hg vapor (Hinton and Viega, 2001). Containment methods are sufficient if the potential for assimilation into the food chain is low. In either situation, long-term management is required until adequate protection of ecological and human health is ensured.

An engineering approach, as described by Greg Reller, explains some of the decisions that are made as part of the remediation process:

- Site-characteristic features are identified by gathering enough information to understand how the site affects the environment and then comparing the information to the regulatory standards or criteria.
- Such remediation measures are identified by considering what technologies have worked at similar sites in the past and by looking for creative or innovative technologies that may be effective at the site.
- Benefits and drawbacks of each technology are then compared to arrive at a decision.
- Total costs are based on the components of the remediation. These components include design, field engineering, construction management, mobilization, demobilization, site preparation, labor, materials, startup, and operations and maintenance.

Other categories and factors influencing remediation costs for mine sites are listed in table 13. This list is not intended to be inclusive (EPA, 1997).

Table 13. Factors influencing remediation costs at mine sites (EPA, 1997)

Category	Factors
Remediation goals	Level of cleanup required
Waste characterization sampling	Type and volume of material and waste, number and frequency of sampling events
Water quality	Degree of contamination: water and sediments
Site characteristics	Size of operation, site access, climate, geologic materials, elevation, topography
Liners	Soil, clay, amended soil, synthetic
Site hydrology	Precipitation, flow rate, water controls
Water treatment	Type of treatment, volume, management of treatment residuals, length of time required
Site operations	Effect on production; time to achieve remediation goals; total ore and waste rock tonnage; extent of site impacts; earthwork requirements, labor, imported material
Regulatory considerations	NPDES, CERCLA, dam safety requirements, local regulations
Water-quality monitoring	Number of analyses, laboratory

	analysis, size of area to be monitored, number of sampling stations, ground-water monitoring
Reclamation requirements	Area to be revegetated, type and amount of cover materials, feasibility and duration, post-reclamation land use

As explained in the previous section, project costs are site specific and based on parameters, such as the type of remediation technology selected, the size of the affected area, the characteristics of the contaminants, the required cleanup standards, the level of health and safety protection required during the remediation, the type and number of chemical analyses, and any long-term, postremedial actions required. Any one of these factors can have a significant impact on the final cost of remediation. Careful consideration of site-specific factors is essential in achieving an accurate cost estimate (EPA, 1997). EPA's Office of Solid Waste report, "Costs of Remediation at Mine Sites," summarizes different actions, costs, and mine remediation projects. Additional unit cost estimates for waste-pile mine remediation are shown in appendix E.

B. Guidance to Documenting Costs for Remediation Projects

Some Federal documentation does exist that provides guidance for engineering firms to predict remediation costs. For instance, an interagency group consisting of the U.S. EPA, Department of Defense, Department of Energy, and Department of the Interior developed a standardized work breakdown structure (WBS) for remediation projects. The use of the WBS "will facilitate comparison of costs across projects, and the detailed breakout will help support extrapolation of costs to future applications" (FRTR, 1998). Cost elements are grouped temporally: before treatment (mobilization, preparatory work, site work, ground and surface water collection), treatment (chemical, physical, biological, thermal), and after treatment (disposal, restoration).

The WBS format uses data collected as part of Federal procurements for site remediation services and stored electronically in a historical cost analysis system. Other software packages that aid engineers include the Remedial Action Cost Engineering and Requirements System prepared by Delta Research Corporation and Cost of Remedial Action, a computer cost program prepared by CH2M Hill. Some remedial action decision support system packages are listed in table 14.

Table 14. Remedial action decision support system packages (Sullivan and others, 1997)

BIOSVE (Biodegradation, Spoil Vapor	RAAS (Remedial Action Assessment System)

Extraction and Vacuum Enhanced Recovery	
CURE (Cost Uncertainty in Remediation Engineering)	RACER (Remedial Action Cost Estimation
MARS (Multiphase Area Remedy Selection)	SELECT (Remedy Selection)

VII. Remediation Control Options And Strategies

Predicting remediation costs and contingency costs for various mercury control operations is very difficult because of the site-specific nature of mercury remediation.
However, mercury control strategy alternatives can be assessed through different criteria to help decisionmakers choose the control option that will give them the best opportunity to meet standards or objectives at the lowest cost.

A. Hydraulic Mine Site Strategies

This section will evaluate various remedies for hydraulic mine sites that exhibit mercury contamination in soil, sediment, and surface water. These remedies are explained in a report prepared for the USFS entitled "Hydraulic Mine Site Mercury Contamination Site Characterizations and Removal Action Considerations" (DeGraff, 2002). Although mine site characteristics and operations vary, most sites have several features in common: a pit lake, a pit wall, a wetland, a sluice cut, and drain tunnels. The report describes each of these features in detail. Table 15 summarizes these characteristics and remedial options.

Table 15. Hydraulic mine site characteristics and remedial options (CDM, 2002)

Feature	Characteristics	Remedial options
Pit lake	Estimated volume of water to be treated; total and MeHg concentrations; other water-quality parameters; size distribution and depth of contaminated sediment; topography; position of site; flow rate; drainage; characterization of subsurface/bedrock	Mechanical moving; suction method; capping; traditional landfill design; evapotranspiration cover; solidification/stabilization; breaching wall; recontour site
Wetland	Regulatory consideration; size and area of wetland; determination of sources/pathways; mercury levels in sediment	Install French drain; fill wetland to match adjacent contours; diversion surface channels
Pit Wall	Scale-height, width, volume of material at risk; stability; pitwall structural composition; determination whether Hg contamination exists	Blasting; soil nailing; retaining wall/sheet piling/timber lagging
(A) Tunnel and Shafts; (B) Surface Sluice Cuts	Depth, volume, and size distribution of bottom sediments; condition of bedrock forming floor and walls in tunnels; extent and level of Hg contamination in sediments; location and accessibility of tunnels	(A) Daylight tunnel; mechanical removal; hydrowash; liner; stabilization/solidification; (B) mechanical moving; grout sediments in place; fill channels with soil/grout mixture; diversion surface channels
Other	Role of site in drainage of entire watershed	Seal openings; breaching mine pit; drill diversion tunnel; pipelines

There have also been emerging chemical and biological remedial technologies for hydraulic mine sites. Chemical measures include using iron oxides in laterite crusts to reduce the mobility of mercury in soil by oxidizing the mercury, using commercial reagents for metal removal, applying eletrokinetic remediation, using an electrical current in a vitrification process to solidify/stabilize mercury, and implementing an aeration system in anoxic areas that are hotspots for the mercury methylation (CDM, 2002). Biological measures include phytoremediation, phytoextraction, phytostabilization, and microbe usage. Appendix F provides information on equipment needed for various remedial options, along with unit costs.

B. General Remediation Control Strategies

Various remediation control strategies for mercury can be assessed using several criteria, such as the accessibility of mercury contamination, data efficiency, and the potential benefits and impacts of controls and sources. As a result of declining budgets, the expected relative cost of the mercury control strategy is important. Another important variable is the degree to which the mercury is accessible for cleanup; that is, whether the mercury is localized and concentrated or diffuse and widely distributed. The quantity and quality of data are important in assessing such situations. Expected benefits of implementing the control strategy are important factors in choosing between various strategies as well. Significant benefits include the estimated percentage of mercury loads removed (or controlled) by source controls and significant increases in beneficial uses.

In choosing a control strategy, one must also take into account the potential environmental or economic impacts associated with the strategy implementation. For example, LWA (1997) evaluated and developed <u>subjective</u> rankings of various remediation control strategies. Table 16 is an example of control strategy evaluation criteria.

Table 16.

Summary of control strategy evaluation criteria

	Control strategies		
Evaluation criterion	1 (best)	2	3 (worst)
% of inplace Hg sources removed or controlled	> 50%	25 - 50%	0%
Are Hg source data sufficient to implement strategy?	Existing information is sufficient	Some additional data are needed	Extensive additional data needed
Limitations of strategy	Minor	Moderate	Severe
Impacts: Environmental and economic impacts of implementation	No significant impacts expected	Potentially significant impacts expected	Severe environmental or economic impacts expected
Decrease in study area Hg loads and concentrations	Significant decrease in Hg (> 25%)	Moderate decrease in Hg (< 25%)	No long-term decrease in Hg expected
Relative cost per unit of Hg controlled	<u>Low cost</u> per kg of Hg controlled	<u>Moderate cost</u> per kg of Hg controlled	<u>High cost</u> per kg of Hg controlled

Control strategies reviewed in LWA's report include PS controls (water treatment for mercury removal), mercury reduction programs (recycling), various mine remediation strategies (stabilization and reclamation of hydraulic mining tailings, removal of hydraulic mining tailings, additional regulation of gold mining activity), and sediment management (stream channel dredging, reservoir dredging, reservoir operational changes). These strategies were evaluated using the criteria above and then ranked. For the results of these rankings, please refer to LWA's report. Additional criteria when estimating costs, such as human health, risk, and methylation reduction are also important indicators when assessing and implementing a remedial strategy.

C. Remediation Cost Strategy

Most cost estimates that have been shown in this document have been from engineers. Project costs are very site specific and are based on a number of parameters, such as type of contaminant, type of remediation technology selected, size of the affected area, characteristics of the contaminants, required cleanup standards, and so on. Agencies use these characteristics and break them down into different cost elements (FRTR, 1998).

Others use a methodology to estimate costs that relies on a variety of cost worksheets under categories such as source control, active treatment, passive treatment, general treatment and polishing, and discharge methods (Tetra Tech, 2000). Costs are usually broken down into capital (one-time costs occurring at the beginning of a project: construction, equipment, and installation) and operating costs (recurring costs; costs associated with doing the work necessary to obtain required remediation levels, labor, and so on). Using these worksheets, although used consistently throughout engineers' work lives, is very time and resource intensive. Several software packages currently in use are helping engineering companies estimate remediation costs (for instance, the Remedial Action Cost Engineering and Requirements system). However, the costs of these systems, the upfront costs of purchasing the equipment, and the time and effort to estimate hundreds of various sites may be too burdensome.

An econometric approach to estimate remediation costs is an alternative solution in predicting remediation costs for mercury control. Since there are hundreds of potential remedial solutions for mercury control, some type of tool is needed that can easily predict an average cost estimate with confidence for each of these potential controls. One possible approach would be to create a multivariate regression model of average or total costs that correlates with the physical and location attributes of existing projects. A regression formulation would consist of environmental (X_i) and location attributes (X_j), with a series of fixed–effects variables for mine locations and attributes (D_m)[5]:

$$\text{Total Costs} = f\,(X_i, X_j, D_m)$$

The second step is to collect as much information as possible on current mines and other possible remediation options (for instance, sediment control, geothermal springs, wetland modification). Regression coefficients can be estimated using these data. Cost estimates can be based on these environmental and location attributes. The benefit of using this tool is the ability to predict rough yet confident cost approximations for specific locations without doing a complete engineering analysis. Although this approach has some promise, there have been doubts expressed by engineers who believe that projects are much too site specific to establish such relationships. Such a tool depends on the availability and accuracy of the data.

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[5] A fixed–effect variable is included in the regression to differentiate between abandoned mines as a possible remediation choice (an input that can be measured) and other remedial strategies that are not contributing as much mercury and are not direct loading sources.

VIII. Conclusion

RWQCBs have the challenging task of developing TMDLs for numerous watersheds. The complexity of mercury fate and transport, speciation, and biological consequences does not make this job easier. Applying cost estimates for mercury remediation projects complicates the situation even further. However, compiling information on past, current, and proposed projects reveals some insights into general categories of remediation costs. Numerous mercury technologies, reduction programs, and remediation techniques provide a clearer picture of the types of activities that public or private entities can undertake to reduce the risk of mercury contamination and the associated costs of these activities. Gold and mercury mine remediation, mercury reduction programs, sediment management, and ecosystem restoration projects are all possible solutions with certain advantages and disadvantages. Agencies have to decide which priorities are more important when assessing a potential remediation project, area, technique, and activity.

The purpose of this economic analysis was to show the general costs associated with the various remedial practices that are applicable to mercury sources in the delta and its tributary watersheds. The RWQCB intends to use this information to determine the relative costs for mine remediation projects and other mercury reduction programs.

Appendices

A: Estimated Cost for Final Compliance: Buena Vista Mine (after SECOR, 1999)

Remediation action	Quantity and type of unit	Total cost (TC) ($)	Price deflator 2003 TC ($)	Unit cost (UC) ($)	Price deflator 2003 UC ($)
Office-permitting/design					
Engineering evaluation	1 LS	40,000	43,084	40,000	43,084
Permitting/agency correspondence	1 LS	30,000	32,313	30,000	32,313
Surveying	1 LS	15,000	16,157	15,000	16,157
Health and safety plan	1 LS	1,000	1,077	1,0000	1,077
Engineering design	1 LS	50,000	53,855	50,000	53,855
Subtotal		136,000	146,486		
Onsite engineering/project management					
Prejob meetings	1 LS	5,000	5,386	5,000	5,386
Field technician	42 weeks	126,000	135,715	3,000/wk	3,213/wk
Project management	22 weeks	88,000	94,785	4,000/wk	4,308/wk
Project control	42 weeks	105,000	113,095	2,500/wk	2,693/wk
Field equipment	42 weeks	10,500	11,309	250/wk	269/wk
Photodocumentation	1 LS	500	539	500	539
Subtotal		335,000	473,924		
Site preparation					
Mobilization	1 LS	50,000	53,855	50,000	53,855
Construction staking and field surveys	80 days	80,000	86,168	1,000/ day	1,077/day
Road improvements	1 LS	5,000	5,386	5,000	5,386
Clear and grub	1 LS	20,000	21,542	20,000	21,542
Debris removal	1 LS	20,000	21,542	20,000	21,542
Storm water diversion conduit and pump	1 LS	15,000	16,157	15,000	16,157
Misc. erosion; safety/fire controls	1 LS	25,000	26,928	25,000	26,928
Subtotal		215,000	231,578		

Appendix—A continued

Remediation action	Quantity and type of unit	Total cost (TC)($)	Price deflator 2003 TC ($)	Unit cost (UC) ($)	Price deflator 2003 UC ($)
Ore excavation, segregation, trucking					
Excavation, segregation, loading[5]	150,000 CY	300,000	323,130	2.00/CY	2.15/CY
Trucking to repository	200,000 tons	400,000	430,840	2.00/ton	2.15/ton
Ore dump dewatering/treatment	80 days	8,000	8,612	100/day	107.65/day
Dust control	170 days	85,000	91,554	500/day	539/day
Building demolition	1 LS	300,000	323,130	300,000	323,130
Retort dump final grading/topsoil	2,000 CY	5,000	5,386	2.50/CY	2.69/CY
Verification soil sampling[1]	50 samples	10,000	10,771	200/ sample	215.42 samples
Placement and compaction of ore	150,000 CY	450,000	484,695	3.00/CY	3.23/CY
Subtotal		1,558,000	1,678,118		
Repository construction/ore placement					
Repository earthwork	50,000 CY	200,0000	215,420	4.00/CY	4.31/CY
Repository liner installation[2]	1 LS	275,000	296,203	275,000	275,000
Leachate collection system	1 LS	25,000	26,928	25,000	25,000
Geotextile/geonet	1 LS	130,000	140,023	130,0000	130,000
Protective soil cover	16,000 CY	40,000	43,084	2.50/CY	2.69/CY
Onsite compacted cohesive soil	5,500 CY	22,000	23,696	4.00/CY	4.31/CY
Topsoil	5,500 CY	13,750	14,810	2.50/CY	2.69/CY
Monitoring wells[3]	3 each	6,000	6,463	2,000/each	2154/each
Subtotal		711,750	766,626		
Erosion control of nonacid-generating soil					
Grading/ore segregation/backfill/compaction[4]	100,000 CY	400,000	430,840	4.00/CY	4.31/CY
Sedimentation basin[5]	1 LS	70,000	75,397	70,000	75,397
Cypress Road	1 LS	40,000	43,084	40,000	43,084

diversion/culvert[6]					
Rock-lined conveyance channels	1 LS	40,000	43,084	40,000	43,084
Upper pit seed pipe/culvert	1 LS	35,000	37,699	35,000	37,699
Subtotal		585,000	630,104		

Appendix—A continued

Passive AMD collection and conveyance					
Sump/piping upgrades	1 LS	5,000	5,385	5,000	5,385
Sump installations (2)	2 each	6,000	6,462	3,000 each	3231/each
Subtotal		11,000	11,847		
Constructed wetlands pilot test					
Field technician	48 days	28,800	31,020	600/day	646.25/day
Project management	30 days	18,000	19,388	600/day	646.26/day
Cell construction[7]	1 LS	8,000	8,617	8,000	8,617
Liner/geonet/geotextiles	1,200 SF	1,800	1,938	1.50/SF	1.62/SF
Import/placement of substrate	110 CY	2,750	2,962	25.00/CY	26.93/CY
Piping installation	1 LS	5,000	5,385	5,000	5,385
Water supply storage tank	1 LS	5,000	5,385	5,000	5,385
Water sampling[8]	1 LS	5,000	5,385	5,000	5,385
Subtotal		74,350	80,080		
Lime treatment system decommissioning/pond closure					
Lime treatment system Decommissioning	1 LS	3,000	3,231	3,000	3,231
Sludge removal/dewatering/disposal	5,000 CY	50,000	53,855	10.00/CY	10.77/CY
Verification sampling	15 samples	5,250	5,655	350/sample	377/sample
Upper and lower pond blackfill and compaction	5,000 CY	15,000	16,157	3.00/CY	3.23/CY
Subtotal		73,250	78,898		
Site restoration/final reporting					
Site cleanup/debris removal	1 LS	20,000	21,542	20,000	21,542
Demobilization	1 LS	30,000	32,313	30,000	32,313
Final survey/reporting/as-built plan preparation	1 LS	35,000	37,699	35,000	37,699
Revegetation	1 LS	25,000	26,928	25,000	26,928
Subtotal		110,000	118,482		
SUBTOTAL		3,809,350	6,746,250		
CONTINGENCY	15%	571,402	1,011,939		
TOTAL ESTIMATED CONSTRUCTION COST		4,380,752.50	7,758,188		

Appendix—A continued

Annual operation and maintenance costs					
Site inspections	4 each	2,800	3,016	700/each	754/each
Site operations and maintenance	600 hrs	30,000	32,313	50/hour	54/hour
Basin sediment Removal/disposal[9]	1,000 CY	5,000	5,385	5/CY	5.4/CY
Monitoring well Sampling/analysis[10]	12 each	7,200	7,755	600/each	646/each
Field supplies/repair parts	1 LS	2,500	2,693	2,500	2,693
Subtotal		47,500	51,162		
Contingency	15%	7,125	7,674		
TOTAL ESTIMATED ANNUAL OPERATIONS AND MAINTENANCE COST		54,625	58,836		

1. Selection verification soil samples will be analyzed for pH, priority pollutant metals, acid-generation potential, and primary/secondary nutrients.
2. The repository multilayered liner will include 60 mil HDPE smooth, 60 mil HDPE textured, 40-mil text.
3. At least three monitoring wells will be installed upgradient and downgradient of the repository.
4. Earth quantities presented are preliminary. Final quantities will be included in the engineered design.
5. Construction costs will vary depending on final design constraints.
6. Construction costs will vary pending negotiations with San Luis Obispo County.
7. Earthwork quantities assume a 3-foot-deep wetlands approximately 50 feet long and 20 feet wide. Final grades and elevations of the wetlands will be determined following processed ore removal.
8. Select influent and effluent samples will be analyzed for pH, priority pollutant metals, and chronic/acute toxicity.
9. Cost estimate done for sediment accumulation/removal using the Universal Soil Loss Equation
10. Assumes a minimum of three monitoring wells associated with the repository will be sampled quarterly. Analytical costs may vary from this estimate depending on RWQCB monitoring and reporting requirements

B. Estimated Costs of Remediation Activities to Reduce Mercury in Clear Lake

(after Cooke and Morris, 2002)

Remediation action	No. unit	Total cost (TC) ($)	Price deflator 2003 (TC) ($)	Unit cost ($)
No action: Contaminated sediment is expected to be buried passively under cleaner sediment	None	0 for Hg control activities	0	0
Mine site				
Waste rock controls	2 million CY of rock	19–63 million	19.38–64.3 million	9.5–31.5/CY
Control surface water and runoff	50 million gal/yr	180,000–3.5 million	183,600–3.57 million	0.0036 – .07/gal
Control ground water	130 million gal/yr	22–30 million	22.44–30.60 million	0.17 – 0.23/gal
Total mine site remediation	None	41.2 – 69.5 million	42.02–70.89 million	
Lakebed sediment				
Dredge hot spots in eastern end of Oaks Arm	270 AC	56–230 million	57.12–234.60 million	20,740 – 851,851/AC
Dredge portions of Oaks Arm with Hg > 25 ppm	780 AC	140–930 million	142.8–948.6 million	179,487–1,192,308/AC
Deposit clean fill in Oak Arm where Hg > 50 ppm	270AC	20 million	20.4 million	74,074/AC
Reduce sediment transport by subsurface barriers to reduce wind-driven currents where Hg > 25 ppm	5,000 LF	N/A		
Public outreach and education				
Monitoring to assess progress toward water-quality objectives		$35,000–$50,000 every 5 years and additional $40,000 every 10th year	35,700–51,000 every 5 years	$7,000–$10,000/year

C. Carson River Mercury Mine Site

(after Ecology and Environment, 2000)

Remediation action	**Total cost ($)**	**Price deflator 2003 ($)**
Excavation	350,000	371,420
Transportation and disposal	810,000	859,572
Backfill	260,000	275,912
Revegetation	110,000	116,732
Demolition	60,000	63,672
Well relocation	50,000	53,060
Hillside drainage system	60,000	63,672
Mobilization/demobilization	450,000	477,546
Compliance with Historical Preservation Act	310,000	328,972
Laboratory analysis	40,000	42,448
Subtotal	2,500,000	2,653,006

Project management	**Total cost ($)**	**Price deflator 2003 ($)**
Subcontractor field oversight, report	350,000	371,420
Subcontractor management	13,000	13,796
Work plan development and management	100,000	106,120
Contractor fees	30,000	31,836
Subtotal	493,000	523,172

Direct compensation	Total cost ($)	Price deflator 2003 ($)
Hotel/per diem paid for family relocation	2,000	2,122
Payment to property owners for demolition	130,000	137,956
Rental assistance to displaced tenants	32,000	33,958
Subtotal	164,000	174,036
TOTAL PROJECT COST ESTIMATE	3,200,000	3,350,214

D. Management Plan Costs for Control of Mercury Methylation in the San Francisco Bay Ecosystem

(McFarland and others, 2002)

Area type	Stations and samples	Receiver	Costs ($)
Outside levee (tidal salt marsh & mudflat)	20 stations; 5 samples/station	Sediment (THg and MeHg)	20,000
		Biota (THg)	4,000
Inside levee (ponds, drainage ditches, marshes)	20 stations; 5 samples/station	Sediment (THg and MeHg)	20,000
		Biota (THg)	4,000
Inside levee (grassland)	5 stations; 5 samples/station	Sediment (THg and MeHg)	5,000
		Biota (THg)	1,000
Outside Hamilton Airfield wetland (established salt marsh, primary channels	5 samples; 5 samples/station	Sediment (THg and MeHg)	5,000
		Biota (THg)	1,000

Cost estimates by task

Task	**Description**	**Cost ($)**
Task #1: Relationships between MeHg and wetland type		
	Labor	81,712
	Travel/boat time	67,917
	Supplies	15,918
	Chemical analysis	217,546
Task #2: Risk of methyl mercury trophic transfer		
	Labor	45,632
	Travel/boat time	19,102
	Supplies	7,428
	Chemical analysis	90,202
	Microbial analysis	23,346
Task #3: Mitigation by wetland plants		
	Labor	212,240
	Travel/boat time	8,490
	Supplies	59,427
	Chemical analysis	117,793
	Microbial analysis	167,670
Task #4: Microbial control of methylation/demethylation rate		
	Labor	182,526
	Supplies	49,876
	Microbial analysis	42,448
General costs		
	Final reporting/printing	13,265
	Travel for meetings in San Francisco	29,714

E. Waste Pile Mine Remediation Costs

(after MEND, 1995)

1. Range of estimated costs of engineered solutions for acid rock drainage for waste rock piles (U.S. dollars/ton of waste)[a]

Remedial technology	Cost ($)
Diversion ditches and berms	1.00/yd^3 material moved –5.00/yd^3 material moved [b]
Collect and treat	0.02–0.14 [b] 0.24–0.57 [c]
Collect and treat with soil cover	0.14–0.49 [b] 0.30–0.77 [c]
Composite soil cover	0.81–1.02 [b] 0.97–1.18 [c]
Synthetic liner (200-year life)	9.36 yd^2–46.8 yd^2 [c]

[a] The values shown include only direct costs and not legal or permitting expenses

[b] Capital unit costs

[c] Final unit costs

2. Range of estimated costs of engineered solutions for acid rock drainage for tailings (U.S. dollars/acre of tailings footprint)[a]

Remedial technology	**Cost ($)**
Collect and treat	153,231–239,188 [b] **528,704–588,359** [c]
Collect and treat with soil cover	224,582–450,335 [b] **494,783–652,693** [c]
Composite soil cover	46,788–759,135 [b] **56,146–1,025,827** [c]
Synthetic liner (200-yr life)	52,632–734,572 [b] **59,655–998,924** [c]

[a] Upper estimates are capital costs, lower estimates are final costs.

[b] Capital unit costs

[c] Final unit costs

3. Costs to treat acid rock drainage (dollars/gallon/minute flow)

Remedial technology	**Range of average capital cost**	**Range of average annual operating costs**
Lime precipitation	$3,322–7,331/gal/min [a]	$802–4123/gal/min [a]
Evaporation	$2,290–6,872/gal/min	$229–2520/gal/min
Passive wetland	$3,322–21,190/gal/min [a]	$137–481/gal/min [a]

[a] (Gusek, 1995)

F. Unit Costs of Remedial Options for Hydraulic Mines

(after CDM, 2002)

Remedial option	Equipment	Unit costs (2003 deflator costs) ($)
Mechanical moving	Bulldozer	600 (612) – 1,620 (1,652) /day
	Front-end loader	840 (857) – 1,400 (1,428) /day
	Track excavator	400 (408) – 700 (714) /day
	Scrapers	960 (979) – 1,700(1,734) /day (23–31 CY capacity)
	Sheepsfoot compactor	600 (612) – 900 (918) /day (300 Horsepower)
	Water truck	600 (612) – 1200 (1224) /day (3,200–5,000 gallons)
	Track-mounted drill; blasting supplies; offroad haul trucks	N/A
Suction	Vacuum truck	800 (816) – 1,200 (1,224) /day (5,000 gallons)
	Portable dredge	N/A
Capping	Bulldozer; front-end loader; track excavator; offroad trucks; sheepsfoot roller	Costs above
	Motor grader	560 (571) – 900 (918) /day (14-ft blade)
	1. Low permeable soil; 2. Geotextile clay liner; 3. Geomembrane	1. 7–10/CY 2. 0.80–2.00/SF (material only) 3. 0.40–0.90/SF (material only)
	Hydroseeder	1,500 (1,530) – 2,000 (2,040)/AC
	Native vegetation seed mixture	N/A
Solidification/ stabilization	Jet grouting (hydraulic mixing)	150 (153) – 225 (230)/CY (inc. labor)
	Soil mixing (mechanical mixing	40 (41) – 100 (102)/CY (inc. labor)
Diversion channel	Bulldozer; motor grader; excavator;	Costs above
	Backhoe w/ rock hammer	300 (306) – 400 (408) /day
	Blasting supplies	Casting: 3.00-6.00/CY; channel excavation: 8.00-12.00/LF
French drain	Excavator; geotextile;	Costs above
	Clean aggregate	8.00-14.00/ton (1 ½ in)
	Perforated pipe	9.00-18.00/LF (installed cost)
Recontour site; berms	Bulldozer, front-end loader, track excavator; scrapes; offroad trucks; water truck	Costs above
Breach mine site	Bulldozer; track excavator; drill;	Costs above
	Gas-powered centrifugal and pump/hoses	350 (357) – 500(510) /day
	Microtunneling	500 (510) – 750 (765) /ton (inc. labor)
Slurry wall	Installation	4.00 – 5.00/SF
Blast casting	Bulldozer; track-mounted; drill, and blasting supplies	Costs above
Soil nailing	Soil nailing	40 (41) – 100 (102) /CY
	Cut and fill (with compaction)	3.00-6.00/CY

Appendix F—continued

Remedial option	Equipment	Unit cost (2003 price deflator costs) ($)
Reinforcement	Retaining wall/timber lagging	35 (36) – 60 (61)/SF
Dewatering drainage control	French drain, fill wetland, diversion surface channels; dewater wetland with evapotranspiration	Same as reinforcement costs
Dewatering	Vegetation; backhoe, shovels	Costs above
Mechanical excavation/transport	5 CY underground loader	750 (765) – 900 (918) /day
	Overshot mucker	480 (490) –600 (612) /day
	Installation of rail track for overshot mucker	18.00-25.00/LF
Hydrowash	Water truck, pump, hose	Costs above
Containment: jet grouting, seal openings, diversion channels, material screening; hydraulics: tunnels, pipes	Bulldozer, excavator, front end loader, low permeable soil, backhoe, blasting supplies, motor grader	Costs above

Other unit costs

Equipment	Costs (2003 price deflator costs) ($)
Dump truck	500 (510) – 700 (714) /day (10 CY capacity)
Articulated dump truck	900 (918) – 1,100 (1,122) (30 CY capacity)
Water wagon	200 (204) – 350 (357) /day (high-pressure pump)
Standard processing equipment	4.00-12.00/CY
Water treatment – filtration	200 (204) – 500 (510) /day (assumes rental or simple filtration equipment only)
Water treatment clarification	60 (61) – 100 (102) /day (assumes use of retention pond and addition of flocculant)
Labor costs	
Superintendent	37 (38) – 45 (46) /hour
Operator	22 (22) – 38 (39) /hour
Laborer	18 (18) – 25 (26) /hour

Disclaimer: These prices do not include mobilization, labor, additional transport costs (road construction), health and safety, disposal, design and initial planning, site characterization, postmonitoring, final reclamation, laboratory tests, and best management practices affiliated costs.

References Cited

Bender, M.T., 2002, Dentist the menace? The uncontrolled release of dental Mercury, Mercury policy project/tides center, 20 p. [*http://www.mercurypolicy.org/new/documents/DentistTheMenace.pdf*].

Bortolin, Greg, 1999, University of Nevada researchers Misra, Miller ready to continue researching DuPont's acid mine drainage technology: University of Nevada at Reno News, University of Nevada at Reno Web site: v. 2, no. 564, [*http://www.unr.edu/nevadanews/vol2no564.html*].

Bostick, D.A., and K.T. Klasson, 1998, Multiweight isotherm results for mercury removal in upper East Fork Poplar Creek water: Oak Ridge, Tenn., Oak Ridge National Laboratory. [*http://www.ct.ornl.gov/eds/RTG/tm13582.pdf*].

Boyce, P.K., Almskog, K.E, and Grosser, P.W., 1999, Much ado about mercury: evaluation of treatment options for mercury contaminated soil at BNL. [*http://phisotopes.ess.sunysb.edu/lig/Conferences/Abstracts99/boyce.htm*].

CALFED Bay Delta Program, 2002, ecosystems restoration, notice of intent to award grants: [*http://calfed.ca.gov/Programs/EcosystemRestoration/ adobe_pdf/Notice_of_Intent_to_Award_Grants204.pdf*].

Carollo Engineers, 2002, Treatment feasibility costs: Sacramento Regional County Sanitation District, Sacramento River wastewater treatment plant 2020 Master Plan.

CDM, 2002, Hydraulic mine site mercury contamination site characterizations and removal actions considerations: Nevada City, Calif., USFS, Tahoe National Forest.

Cooke, J., and Morris, P., 2002, Amendment to the water quality control plan for the Sacramento River and San Joaquin River basins for the control of mercury in Clear Lake (Lake County) functionally equivalent document: Sacramento, Calif., Central Valley Regional Water Quality Control Board, mercury TMDL unit, staff report.

CVRWQCB, 2001a, Clear Lake TMDL for mercury staff report: Sacramento, Calif. Regional Water Quality Control Board Central Valley Region Draft Final Report.

CVRWQCB, 2001b, Sacramento-San Joaquin Delta Estuary TMDL for Mercury – Problem Statement: Sacramento, Calif., Central Valley Regional Water Quality Control Board (CVRWQCB), mercury TMDL unit, staff report. [*http://www.swrcb.ca.gov/rwqcb5/programs/tmdl/deltahg.html*]

DeGraff, J.V, 2000, On-scene coordinator report, removal action for the Gibraltar mine and mill, Santa Barbara ranger district: USFS, Los Padres National Forest.

DeGraff, J.V., 2002, Removal preliminary assessment for the Sailor Flat (East) Hydraulic Mine Site, Nevada City RD: USFS, Tahoe National Forest.

Dynaphore, Inc., 2002, Cost Comparisons. [*http://www.dynaphore.com/costdetails.htm*]

Ecology and Environment, Inc., 1999, Non-Time-Critical Removal Action: Santa Barbara, Calif., Gibraltar Mine Site.

Ecology and Environment, Inc., 2000, Remedial actions report: Carson River mercury site operable unit 1–surface soil Dayton and Silver City, Nevada, prepared for U.S. EPA Region IX.

EPA, 1994, ARCS remediation guidance document: Chicago, Ill., EPA 905-B94 -003, Great Lakes National Program Office. [*http://www.epa.gov/glnpo/arcs/EPA-905-B94-003//B94-003.cov.html*]

EPA, 1995, Contaminants and remedial options at selected metal contaminated sites: Columbus, Ohio, Contract No. 68-C0-003 work assignment 41, EPA National Risk Management Research Laboratory.

EPA, Office of Solid Waste, 1997, Costs of remediation at mine sites. [*http://www.epa.gov/epaoswer/hazwaste/ldr/mine/costs.pdf*]

EPA, 1997, Mercury study report to Congress: An evaluation of mercury control technologies and costs, v. 7.

EPA, 2000, Superfund Fact Sheet, Polar Star Mine tunnel: EPA removal action fieldwork to start in may, EPA Region IX. [*http://yosemite.epa.gov/r9/sfund/fsheet.nsf/024bc4d43f9aa0f48825650f005a714e/c2e2a4d3d0df030d8825691900728067/$FILE/PolarStar4_00.pdf*]

EPA, 2002, Superfund Fact Sheet, Sulphur Bank Mercury Mine, EPA Region IX. [*http://yosemite.epa.gov/r9/sfund/overview.nsf/507c94f730e0ebf488256958005cda5f/732516dbab72412b8825660b007ee679?OpenDocument*]

Federal Remediation Technologies Roundtable, 1998, Guide to documenting cost and performance for remediation projects, prepared by member agencies of the Federal remediation technologies roundtable. [*http://costperformance.org/pdf/guide.pdf*]

Federal Remediation Technologies Roundtable, 2000, Abstracts of remediation case studies: v. 4. [*http://costperformance.org/pdf/abstractsvol4.pdf*]

Fuller, Amanda, 2002, Addressing the environmental mercury problem in watersheds: remediation in the Guadalupe River water, San Jose, Calif., *in* The environment: studies of ecological interconnections, Latto, J. , Orr, M., Desai, M., and Remais, J., senior research seminar: University of Berkeley, Calif. [*http://ist-socrates.berkeley.edu/~es196/projects/2002final/Fuller.pdf*]

Gusek, J., 1995, Passive treatment of acid rock drainage: what is the potential bottom line?: Littleton, Colo., Mining Engineering.

Hinton. J., and Viega, M., 2001, Mercury contaminated sites: a review of remedial solutions, *in* NIMD (National Institute for Minamata Disease) Forum 2001, Minamata, Japan. [*http://www.facome.uqam.ca/facome/pdf/Minamata_Forum_2001.PDF*]

Johnson, Bill, 2000, Mercury reduction menu, EIP Associates, Technical Memorandum prepared for Don Birrer (Bay Area Dischargers Association), Selina Louie (San Francisco Bay Regional Water Quality Control Board), and Stephanie Hughes (Palo Alto Regional Water Quality Control Plant).

Kaplan, D.I., Knox, A.S., and Myers, J., 2002, Mercury geochemistry in a wetland and its implication for in–situ remediation: Contract no. DE–AC0996SR18500, U.S. Department of Energy.

King, J.K, Gladden, J.B., Harmon, S.M., Fu, T.T., 2001, Mercury removal, methyl mercury formation, and sulfate reducing bacteria, profiles in wetland mesocosms containing gypsum–amended sediments and *scirpus californicus*. Westinghouse Savannah River Company TR-2001-00063.
[*http://www.srs.gov/general/pubs/fulltext/tr2001063/tr2001063.html*]

Larry Walkers Associates (LWA), 1997, Sacramento River mercury control planning final project: prepared for Sacramento Regional County Sanitation District.

Lawler, David, 2001, Abandoned mine lands program Bear-Yuba watershed, proposed Boston mine site remediation plan, draft version: received from Bureau of Land Management (BLM) California State Office in September 2002.

Lunceford, Sandra, 2001, Policy approaches to California’s mercury legacy: master’s thesis: Sacramento, Calif., California State University.

Mahaffey, Kathryn R., 1998, Methyl mercury exposure and neurotoxicity: Journal of American Medical Association: v. 280, no. 8.

McFarland, V.C., and others, 2000, Development of a management plan for the control of mercury methylation in seasonal and tidal wetlands construction in the San Francisco Bay system: Vicksburg, Miss., USACE Engineer research and development center, waterways experiment station.

McFarland, V.C., Clarke, J.C., Lutz, C.H., and Macmillan, D.K., 2002, Mercury concentrations bordering the Hamilton Army Air Field remediation site: September 2001: Vicksburg, Miss., USACE Engineer Research and Development Center, Waterways Experiment Station.

MEND, 1995, Economic evaluation of acid mine drainage technologies, mine environment neutral drainage program, Report 5.8.1, Ottawa, Ontario, Canada Center for Mineral and Energy Technology.

Minnesota Pollution Control Agency, 2000, Options and strategies for reducing mercury release: Report to the advisory council of the Minnesota pollution control agency mercury contamination reduction initiative, from the source reduction feasibility and reduction strategies committee. [*http://www.epa.gov/glnpo/bns/mercury/Draft_Report_for_Mercury_Reduction_Options.pdf*]

National Center for Environmental Research, 2001, Small business innovation research, final report, low cost in–situ technique for mercury removal. [*http://es.epa.gov/ncer/final/sbir/00/remediation/rainer.html*]

Nelson, E.A, Specht, W.L., Bowers, J.A, Gladden, J.B., 2002, Constructed wetlands for removal of heavy metals from NPDES outfall effluent. [*http://www.srs.gov/general/pubs/fulltext/ms2002600/ms2002600.html*]

NYC Wasteless, 2001, The port authority of NY and NJ at LaGuardia airport, fluorescent lamp recycling program. [*http://www.nycwasteless.com/gov-bus/Casestudies/lgacase1.htm*]

PCA Water Code 13241, 2003, California Porter-Cologne Water Quality Control Act.

Ross and Associates, 2000, Great Lakes binational toxics strategy draft report for mercury reduction options: prepared for EPA Great Lakes National Program Office Contract #68-W-99-033.

Sacramento Regional County Sanitation District, 2001, work plan for reducing pollutant loads to the Sacramento River: Sacramento regional wastewater treatment plant, produced in association with Larry Walkers Associates and Carollo Engineers.

SECOR International, Inc., 1999, Final compliance plan: Buena Vista Mine, San Luis Obispo County, Calif.: Buena Vista Mines, Inc.

Slotton, D.G. and others, 2002, The effects of wetland restoration on the production and bioaccumulation of methyl mercury in the Sacramento–San Joaquin Delta, California, submitted in collaboration with the multi-institution directed action research project: assessment of ecological and human health impacts of mercury in the San Francisco Bay-Delta watershed, CALFED bay-delta program project, draft final report.

Smelser, M.G., and Whyte, D., 2002, Remediation of the Gambonini mercury mine: Marin County, Calif., engineering geology practice in northern California, California Geological Survey.

Smith, Barbara F., 2002, Removal and stabilization of mercury from mixed waste debris using polymer filtration technology: Northeast Waste Management Officials' Association, Mercury Program.

[*http://www.newmoa.org/Newmoa/htdocs/prevention/mercury/breakingcycle/compendium/BSmith.pdf*]

Sullivan, T.M., Gitten, M., and Moskowitz, P.D., 1997, Evaluation of selected environmental decision support software: U.S Department of Energy, Office of Environmental Management.

Suter, Daniel, 2001, Pollution report, Buena Vista/Klau Mercury Mine Site: San Luis County, Calif., EPA Region IX.

Tetra Tech, Inc., 2000, Methodology for estimating the costs of treatment of mine drainage: Pittsburgh, Penn., prepared for U.S. Office of Surface Mining.

Tinsley, Nikki, 2002, EPA, Inspector General letter to Congressman John D. Dingell, Ranking Member, Committee on Energy and Commerce U.S. House of Representatives. [*http://www.envinfo.com/july/2002/DingellFinal.pdf*.]

U.S. Army Environmental Center, 1997. [*http://aec.army.mil/usaec/publicaffairs/update/spr97/lamp.htm*]

U.S. Department of Energy, 1999, Mercury contamination-amalgamate

(contract with NFS and ADA), stabilize elemental mercury wastes: Innovative

Technology Summary Report, DOE/EM-0472.

[*http://apps.em.doe.gov/OST/pubs/itsrs/itsr1675.pdf*

U.S. Department of Energy, 1999, Demonstration of ATG process for

stabilizing mercury (<260 ppm) contaminated mixed waste: Innovative

Technology Summary Report, DOE/EM-0479.

[*http://apps.em.doe.gov/OST/pubs/itsrs/itsr2407.pdf*]

USFS, 2002, Final report preliminary assessment Buckeye Diggins Hydraulic Mine: prepared by CDM Federal Programs Corporation for USDA Forest Service, Tahoe National Forest.

USFS, 2003, Action Memorandum, nontime-critical removal action at Sailor Flat (East) Hydraulic Mine Site, received by Rick Weaver.

Vassey, S.K., 1999, Economic considerations in TMDL development and basin planning, Calif.: State Water Resources Control Board, *in* EPA Region IX guidance for developing TMDLs in California, Appendix A, January 7, 2000. [*http://www.epa.gov/region09/water/tmdl/caguidefinal.pdf*]

Weiner, J.G., Gilmour, C.C., and Krabbenhoft, D.P., 2003, Mercury Strategy for the Bay Delta ecosystem: a unifying framework for science, adaptive management, and ecological restoration: Draft final report to CALFED.

Weiss, Julie, 2003, City of Palo Alto residential fluorescent lamp recycling program: City of Palo Alto regional water quality control plant. [*www.city.palo-alto.ca.us/cleanbay*]

Wood, Alexander, 2003, Cost Data for the Economic Analysis of the Sacramento–San Joaquin Delta Estuary Mercury TMDL: U.S. Geological Survey, report prepared for Regional Water Quality Control Board.

Wood, Michelle, 2002, Economic Analysis for the Sacramento–San Joaquin Delta Estuary Mercury TMDL, Scope of Work: Contract No. 00–197–150–0 (Task 8), California Regional Water Quality Control Board.