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By Michael P. Hunerlach, James J. Rytuba, and Charles N. Alpers

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ABSTRACT

Mercury contamination at historic gold mining sites represents a potential risk to human health and the environment. Elemental mercury (quicksilver) was used extensively for the recovery of gold at both placer and hardrock mines throughout the western United States. In placer mine operations, loss of mercury during gold recovery was reported to be as high as 30 percent. In the Dutch Flat mining district located in the Sierra Nevada region of California, placer mines processed more than 100,000,000 cubic yards of gold-bearing gravel. The placer ore was washed through mercury-charged ground sluices and drainage tunnels from 1857 to about 1900, during which time many thousands of pounds of mercury were released into the environment.

Mine waters sampled in 1998 had total unfiltered mercury concentrations ranging from 40 ng/L (nanograms per liter) to 10,400 ng/L, concentrations of unfiltered methyl mercury ranged from 0.01 ng/L to 1.12 ng/L. Mercury concentrations in sluice-box sediments ranged from 600 µg/g (micrograms per gram) to 26,000 µg/g, which is in excess of applicable hazardous waste criteria (20 µg/g). These concentrations indicate that hundreds to thousands of pounds of mercury may remain at sites affected by hydraulic placer-gold mining. Elevated mercury concentrations have been detected previously in fish and invertebrate tissues downstream of the placer mines. Extensive transport of remobilized placer sediments in the Bear River and other Sierra Nevada watersheds has been well documented. Previous studies in the northwestern Sierra Nevada have shown that the highest average levels of mercury bioaccumulation occur in the Bear and South Fork Yuba River watersheds; this study has demonstrated a positive correlation of mercury bioaccumulation with intensity of hydraulic gravel mining.

INTRODUCTION

Mercury is a potent neurotoxin which has a tendency to biomagnify in the food chain (Krabbenhoft and Rickert, 1995) and is a potential threat to human and ecological health. This research documents previously unrecognized point sources that contain hundreds to thousands of pounds of elemental mercury. Our initial assessment provides information with regard to the specific location of mercury sources in the upper Bear River watershed in the Sierra Nevada region of California (fig.1). Mercury-contaminated watersheds affected by historic placer and hardrock gold mining include extensive public lands managed by the Bureau of Land Management (United States Department of Interior) and the Forest Service (United States Department of Agriculture). The present study is designed to provide a baseline characterization of contaminated areas within the Bear River watershed prior to any remediation efforts. The results of this pilot study may be used to develop a cost-effective, watershed-based approach to addressing regional mercury contamination associated with historic gold mining in the Sierra Nevada.

An abandoned mine in the Dutch Flat mining district, California (fig. 1), which is a highly concentrated point source of mercury impacting the Bear River watershed, was identified as part of the current study. Hydraulic mine tailings are known sources of low concentrations of mercury; however, past studies have failed to locate specific sites with extremely elevated elemental mercury, or *hot spots*. Typically, at streams within deposits of Quaternary age that have elevated mercury, demonstrated point sources can be found, and these hot spots correlate

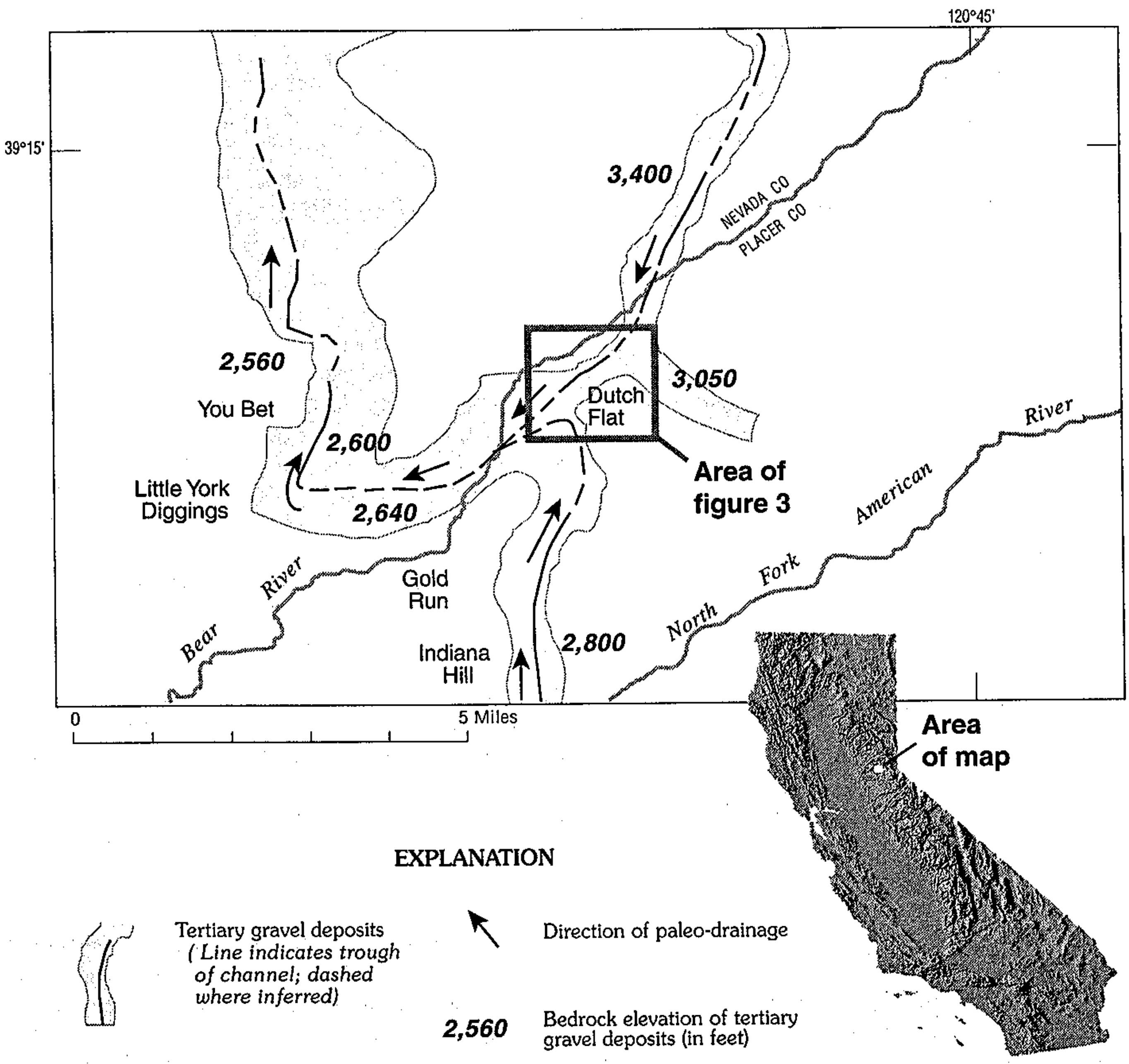

Figure 1. Location map showing trace of Tertiary-age river channels in the ancestral Yuba River (modified from Yeend, 1974), California.

with the location of the river channels of Tertiary age where the extensive gravel deposits were exploited for gold by hydraulic mining and where drainage tunnels, sluice boxes, and underground (drift) gravel mines occur.

There are at least five known sluices that discharged hydraulic mine tailings to the Bear River in the Dutch Flat district. Typical 19th century hydraulic gold mining recovery systems used mercury amalgamation to recover gold. Ground sluices and tunnel sluices from hundreds to thousands of feet in length were charged with hundreds to thousands of pounds of mercury. Some of these sluices remain as well-preserved mining artifacts that are easily accessible and actively visited by local miners who attempt to reclaim gold from the remaining amalgam. This activity can expose large quantities of elemental mercury and associated mercury vapors and may pose human health hazards or environmental hazards to downstream surface waters. Mine tailings and placer sediments at abandoned hydraulic placer-gold mines are abundant and fill numerous drainages, ravines, and benches. The presence of large quantities of elemental mercury associated with these sediments indicates that there is a significant potential risk to surface-water quality.

An extensive regional problem exists in watersheds in the northwestern Sierra Nevada because there are numerous drainage basins where placer-gold mining activities have occurred (Larry Walker Associates, 1997). Information collected for this report will help in evaluating other mercury point sources throughout the many hydraulic gold-mining districts in California and elsewhere in the western United States.

In 1998, the U.S. Geological Survey began a water-quality investigation in the Bear River watershed with the following overall objectives: (1) determine the seasonal variability of mercury loading to the Bear River from tunnel and ground-sluice discharges; (2) determine the distribution of mercury in underground mine workings, hydraulic pits, and sluices by mapping and sampling; (3) assess mercury bioaccumulation in aquatic life; and (4) enhance existing databases with detailed information on the occurrence and speciation of mercury associated with hydraulic mining debris in the Bear River watershed, for use in Geographic Information System analysis and watershed planning.

Purpose and Scope

This report describes a preliminary assessment of the extent of mercury contamination from hydraulic gold mining in the upper Bear River watershed and documents the potential risk to riparian and human health. Data presented include mercury concentrations in water, sediment, and fish tissue; mine discharge measurements; and estimates of total elemental mercury residing in sluice-box sediments. Methyl and total mercury concentrations are reported for selected samples of water (total and filtered) and of sediment to better understand mercury transport and transformation processes.

Acknowledgments

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HYDRAULIC MINING AND MERCURY USE

Placer gold deposits were the first type of gold discovered and mined on a large scale in California. Vast Tertiary-age gravel deposits from ancestral rivers within the Sierra Nevada gold belt region (fig.1) contained large quantities of gold. In 1852, hydraulic mining technology evolved with the use of water canons to deliver large volumes of water that stripped the ground of all soil, sand, and gravel above bedrock. Water was transported through hundreds of miles of ditches, flumes, and pipes up to 36 inches (in.) diameter under pressure of hundreds of pounds per square inch from over 500 feet (ft) of head, and was discharged through a converging 6-to-9 in. nozzle or *monitor.* Powerful jets of water generated through the monitor were used to dislodge and wash away extensive gravel deposits. Some mines operated several monitors in the same pit simultaneously. Hundreds of millions of cubic yards of sediment and water were directed into sluice boxes to separate and recover gold particles by gravity settling. Hydraulic mining was so popular and effective that it outproduced all other types of mining, even by 1900 when hardrock gold mines had been developed throughout the Mother Lode gold belt.

The capability of mercury to alloy with gold has been well known for more than 2,000 years (Rose and Newman, 1986). Mercury was added to large troughs within the sluice boxes to recover the gold as an amalgam. Because such large volumes of turbulent water flowed through the sluices, much of the finer gold and mercury particles were washed through and out of the sluice before they could settle in the riffles. A modification known as an *undercurrent* was developed to address this loss. Essentially a broad sluice, the undercurrent was set on a shallow grade at the side of, and below, the main sluice. Fine-grained sediment was allowed to

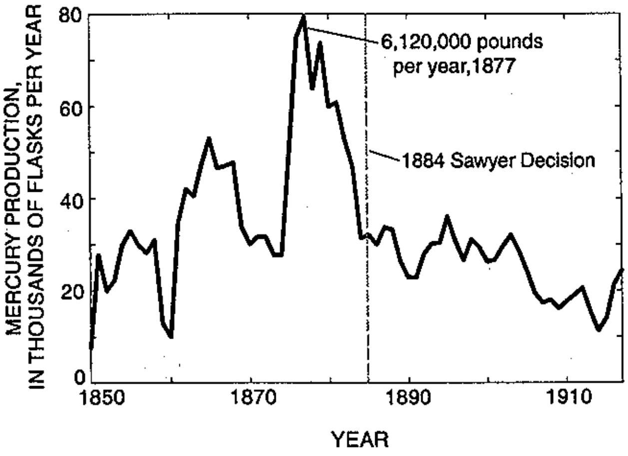

Figure 2. Mercury production from the California Coast Ranges, 1850–1917 (modified from Bradley, 1918). (Prior to 1904, one flask equalled 76.5 pounds; starting in 1904, one flask equals 75 pounds)

drop onto the undercurrent, where gold and amalgam were caught (Averill, 1946). Because this method was so efficient, high profits thus realized from hydraulic operations stimulated mining throughout the Sierra Nevada gold belt region and the western United States.

Most of the mercury used in the amalgamation process was obtained from the Coast Range mercury mineral belt on the west side of California's Central Valley. In 1877, mercury mines in the Coast Range reached a peak production of 6,120,000 pounds (lb) of mercury (Bradley, 1918) (fig. 2). Most of this mercury was used for gold recovery throughout the Sierra Nevada and Klamath–Trinity Mountains in California and elsewhere in the western states.

Mercury was introduced and distributed throughout the entire sluice box. Large troughs built into the sluice held hundreds of pounds of elemental mercury and the entire surface of the undercurrents [as much as 5,000 to 10,000 ft^2 (square feet)] were at times covered with copper plates treated with mercury. Initial charging rates varied at different mines and as a general rule the upper portions of the sluice boxes were most heavily charged with mercury. More than 1,500 lb of elemental mercury were used in a single sluice at the start of each season (Bowie, 1905). As much as 1,300 lb were added every 12 days due to the loss from the pounding and washing of the gravels passing over the liquid mercury. The specific gravity of gravel [2.7 g/cm^3 (grams per cubic centimeter)] is one-fifth that of mercury (13.6 g/cm^3), so the gravel would easily float over the mercury while the gold (19.3 g/cm^3) would sink into the troughs.

Unclassified gravel and boulders that entered the sluices caused the mercury to *flour*, that is, break into minute, dull-coated particles. Flouring was aggravated by agitation or exposure of the mercury to the air, and eventually the entire length of the sluice box would be coated with mercury. Some of the liquid mercury escaped from the sluice box with the tailings and was transported downstream. Some remobilized placer sediments remain close to their source in ravines that drained the hydraulic mines. Bowie (1905) noted that minute globules of quicksilver were reported floating in surface waters as much as 20 miles downstream of mining operations.

It has been estimated by Averill (1946) and others that under the best operating conditions, 10 percent of the mercury used was lost and, under average conditions, the loss of mercury was up to 30 percent. Estimates of mercury usage vary from 0.1 to 0.36 lb/ft^2 (pounds per square foot) of sluice box (Averill, 1946). We estimate that a typical sluice box had an area of 2,400 ft^2 (square feet) and used up to 800 lb of mercury during initial start-up with an additional 100 lb added monthly during its operating season (generally 6 to 8 months depending on water availibility). The annual loss of mercury from a typical sluice was likely to have been several hundred pounds.

HYDROLOGIC SETTING

The Bear River and its tributaries are the primary water resources in the Dutch Flat mining district. Water levels in the Dutch Flat Afterbay fluctuate with the release of water from two hydroelectric powerhouses just upstream of the confluence of the Little Bear River (fig. 3). Both the Bear and Little Bear rivers meander through deeply incised canyons that contain abundant alluvium and terraced placer tailings. Flows into and from the Dutch Flat Afterbay are controlled by the Nevada Irrigation District through a network of forebays, canals, and powerhouse discharges. Flow for the Bear River below the Dutch Flat Afterbay ranged

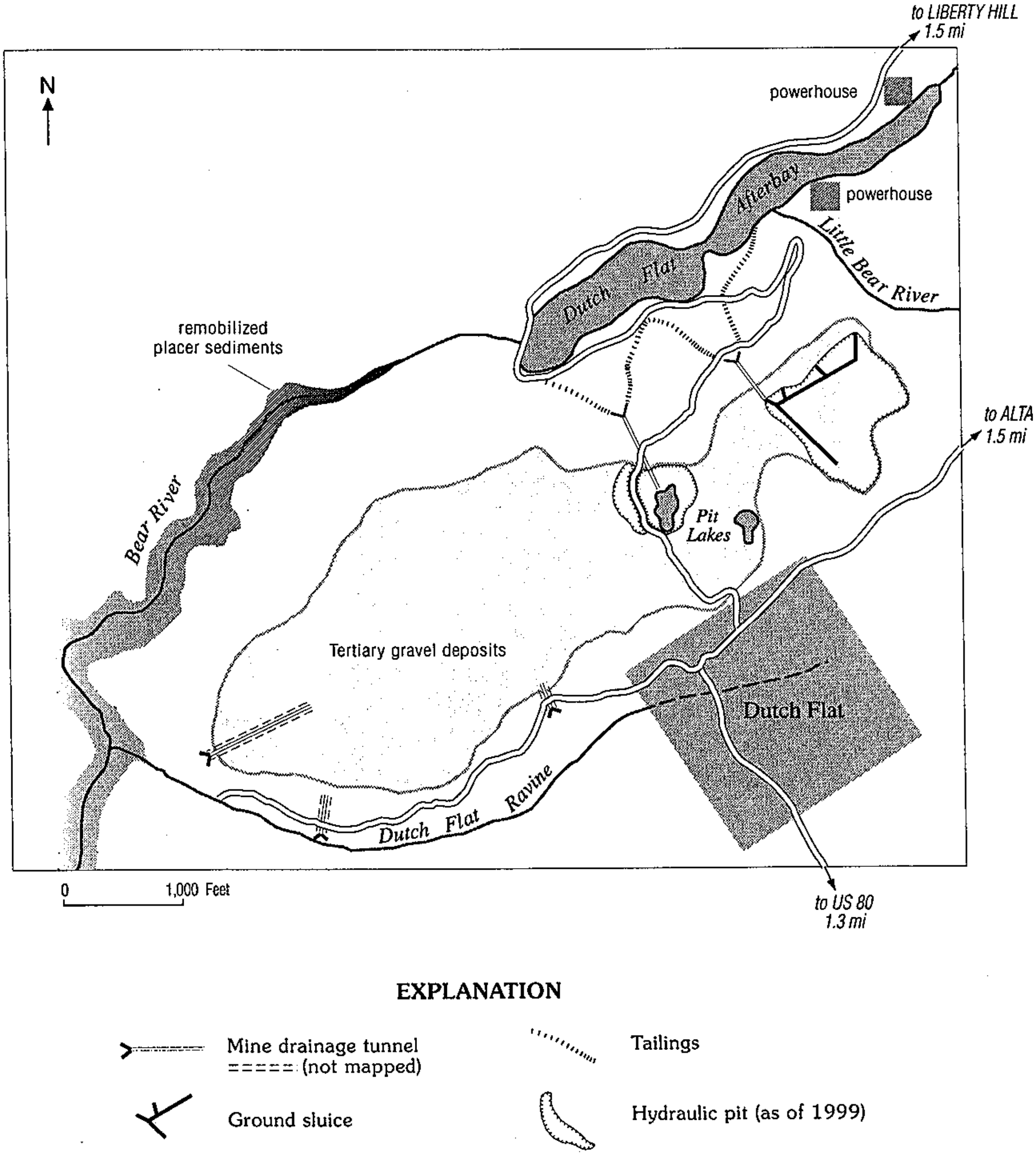

Figure 3. Plan view of Dutch Flat mining district, California.

from 6.9 to 494 ft^3/s (cubic feet per second) for the water year October 1997 to September 1998 (W. Morrow, Nevada Irrigation District, written commun., 1998). The Bear River is tributary to the Feather River, which joins the Sacramento River near Verona and then flows into the Sacramento-San Joaquin Delta and San Francisco Bay (fig. 4).

Geomorphology

Tertiary-age river-channel deposits extend north and south through Nevada and Placer counties of California (fig. 1) (Lindgren, 1911; Yeend, 1974). These quartz-rich, gold-bearing sedimentary channel deposits were part of the large paleodrainage of the Sierra Nevada that was buried

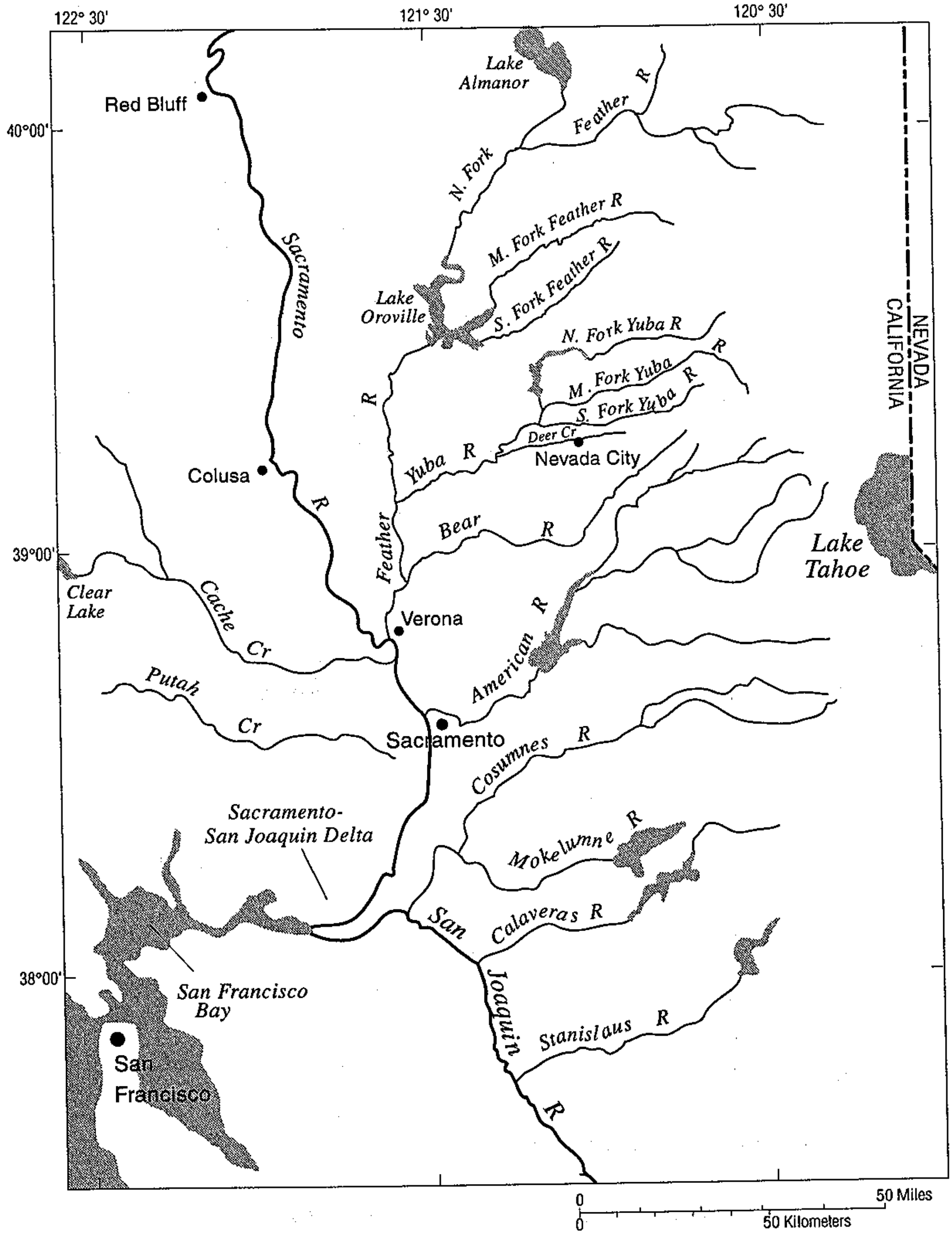

Figure 4. Location map showing selected rivers and reservoirs in the Sacramento River watershed, California.

during the Tertiary by volcanic eruptions and related mudflows. Quaternary-age rivers have cut sharp, V-shaped canyons through the volcanic deposits, exposing cross sections of the Tertiary-age river channels during uplift of the Sierra Nevada. Unexposed portions of the Tertiary-age river channels are covered by volcanic rocks that cap the ridges that divide the rivers of the western slope of the Sierra Nevada.

The Dutch Flat mining district covers about two miles of Tertiary-age river-channel deposits that lie sub-parallel to the present-day Bear River drainage (figs. 1 and 3). The district was one of the largest gold producers in California and was developed along the richest sections of the Tertiary-age channel in Placer County, at the junction where three large segments of the Tertiary-age Yuba River system merged. Remaining unworked gravels in the open pits are semi-circular with vertical banks developed as high as 160 ft. The base of the pits expose bedrock that supports little vegetation except for manzanita bushes and sparse pine trees. Pit lakes locally form in areas where the bedrock forms depressions or was excavated to elevations below the grade of tunnel drainage.

Documentation of hydraulic debris in the Bear River

From 1853 to 1884, unregulated hydraulic mining caused severe aggradation of river channels within the Sierra Nevada with the release of over 1.6 billion yd^3 (cubic yards) of sediment and debris (Gilbert, 1917). Natural drainage carried most of the remobilized gravel to the edge of the Central Valley where it was deposited because gradients in river channels were lower, filling and choking channels. As early as 1867, tailings from placer mines had accumulated to as much as 70-ft thick in the Bear River drainage and had created major problems with flooding of downstream cities and navigation on the Feather and Sacramento rivers (Averill, 1946). After the Sawyer Decision in 1884 (issued by Judge Lorenzo Sawyer against the North Bloomfield Mining Company) hydraulic mining nearly ceased. The Caminetti Act, passed by the U.S. Congress in 1893, allowed mines to operate only if mine operators built approved debris dams.

The Bear River is one of the most environmentally impacted rivers in the Sierra Nevada with more than 254 million yd^3 of gravel and sediment added from hydraulic mining, second only to the much larger Yuba River watershed (Gilbert, 1917). It was estimated that by 1881, more than 105 million yd^3 of gravel had been washed from the mines in the Dutch Flat mining district (U.S Congress, 1881). This figure does not include the deeper gravels washed through the tunnels that were active during the 1880s and 1890s. Drift mining along the gravel–bedrock contact continued after cessation of hydraulic mining with an estimated 30 million yd^3 having been mined in the Dutch Flat district by this method.

We estimate for the period of 1884 through 1901 that more than 50 million yd^3 washed through tunnels in the Dutch Flat district. These sediments entered the Bear River behind a log crib debris dam (since removed, except for bedrock foundation). This dam, jointly used by the Elmore Hill, Nary Red, Polar Star, and Southern Cross mines in Placer County and the Liberty Hill mine in Nevada County, was inundated with debris and sediment that was eventually released down the Bear River when it breached. Much of the coarser material remains along the shoreline and in local ravines whereas finer grained sediments fill wide low-flow sections of the river.

Recent studies (James, 1991) indicate that more than 139 million yd^3 of hydraulic tailings remain stored in the lower Bear River Basin. The sediments released during placer mining in the upper Bear River basin are extensive and their volume is unknown. These sediments are subject to sustained remobilization (James, 1991) which is in contrast with Gilbert's (1917) symmetrical wave model of sediment transport that implied a rapid return of sediment loads to pre-hydraulic mining levels. Recent floods (December 1996 through January 1997) remobilized large quantities of hydraulic mine tailings and sediment in the drainages of the basin, exposing elemental mercury in the stream bed.

MERCURY TRANSPORT AND BIOACCUMULATION

Previous work has documented mercury concentrations as high as 0.33 µg/g (micrograms per gram) in fish tissue (Slotton and others, 1997) and 0.37 µg/g in sediment (Domagalski, 1998) from the Bear River watershed. These compare with background values in uncontaminated areas of less than 0.1 µg/g in fish tissue and 0.06 µg/g in sediments (Porcella and others, 1995; Hornberger and others, 1999). On a watershed scale, we have demonstrated a correlation between mercury bioaccumulation data (Larry Walker Associates, 1997) and volume of gravel hydraulically mined (Gilbert, 1917) (fig. 5). The highest values of bioavailable mercury are found in watersheds that are the most environmentally impacted from hydraulic placer-gold mining.

Previous studies have estimated that substantial amounts of mercury, between 3,300 tons (California Regional Water Quality Control Board–Central Valley Region, 1987) and 10,000 tons (Hornberger and others, 1999), were transported along with remobilized sediment from hydraulic mining to San Francisco Bay. In two San Pablo Bay cores, the isotopic compositions of sediment deposited between 1850 and 1880 (Jaffe and others, 1998) correlate with those found in exposed Tertiary-age gravels at abandoned hydraulic gold mines in the Bear River watershed (Bouse and others, 1996). Mercury concentrations in these core

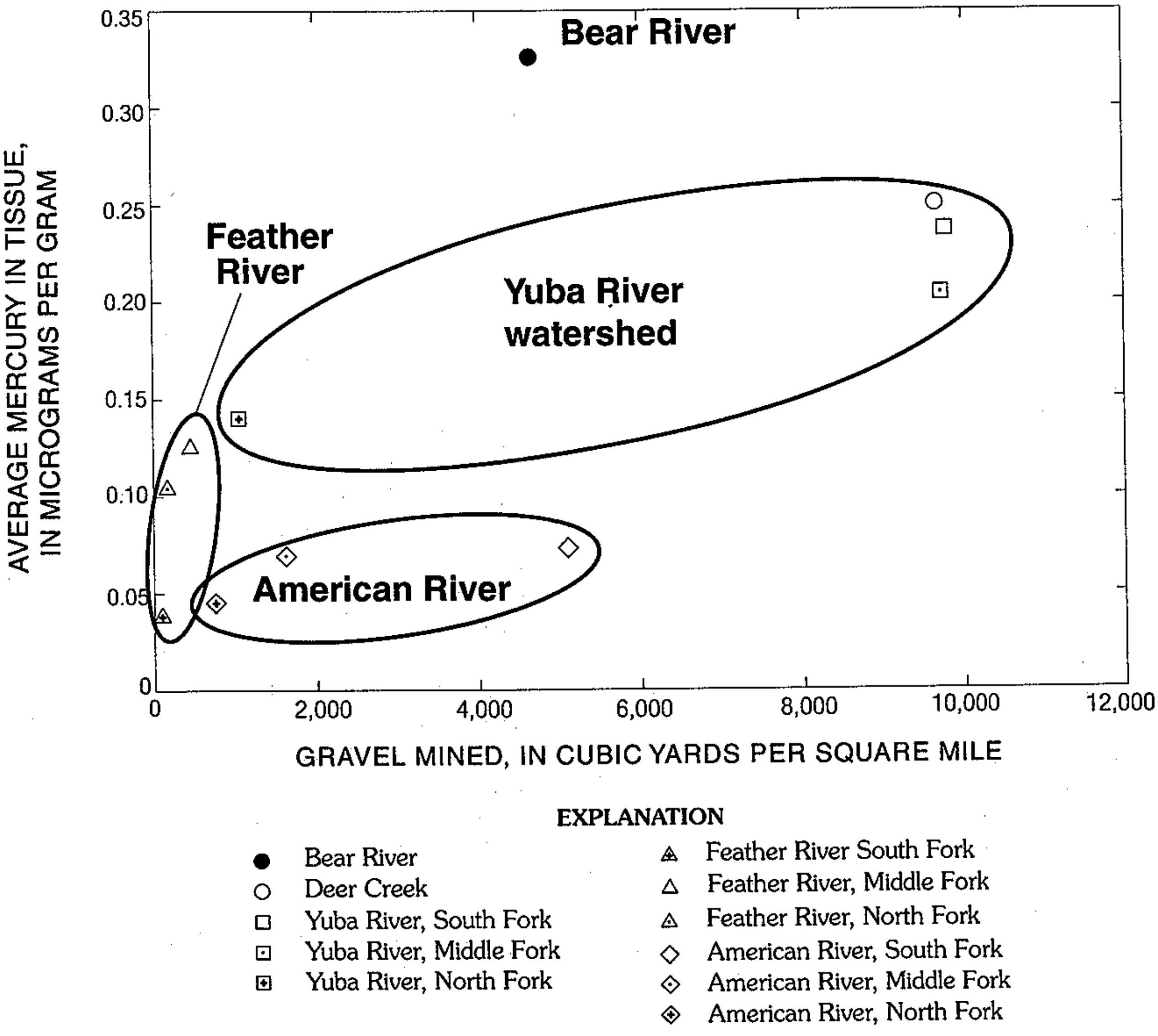

Figure 5. Correlation of yardage mined (normalized to area of drainage basin, in square miles) with average tissue mercury concentration, normalized to an intermediate trophic level (mercury data from Larry Walker Associates, 1997).

sediments range from 0.3 µg/g to 0.5 µg/g. Mercury concentrations as high as 1.2 µg/g have been found in core sediment from Grizzly Bay (Hornberger and others, 1999).

METHODS

Mine drainage waters and sediment were sampled from a historic intact sluice box at an abandoned mine in the Dutch Flat mining district (mine #1) during July and August 1998 and from the portal of another (mine #2) during August 1998. Waters flowing from the portals of these mines were sampled for total and methyl mercury using precleaned bottles provided by Frontier Geosciences Inc. Samples were filtered using an ultraclean 0.45 µm (micrometer) nitrocellulose membrane. Wet gravity separation (that is, panning) was used in the field with a portable balance to estimate the mercury concentrations in the sluice box sediments. Random 1-kg (kilogram) grab samples were weighed, sieved to less than 0.25 in., and panned to separate total recoverable elemental mercury. The mercury was weighed and compared with the initial sample for a gram per kilogram ratio (g/kg). Grab samples were carefully taken from undisturbed top sediments and a specially designed suction tube was used to recover deep sediments at the bedrock contact. Fish collection was done by electrofishing a quarter-mile reach of the Dutch Flat Afterbay (fig. 3). Trout collected from the Dutch Flat Afterbay by USGS personnel were analyzed for total mercury in fillets by the California Department of Fish and Game's laboratory in Moss Landing, California.

RESULTS

Field reconnaissance identified numerous drainage tunnels, bedrock cuts, and ground-sluice remains, all of which contain visible mercury in the Dutch Flat district. In one drainage tunnel an original intact sluice box was identified. Initial results using pan concentration and a portable scale showed as much as 30 g (grams) of elemental mercury from 1 kg of carefully selected sluice-box sediment.

Mercury in mine-drainage waters

Total mercury concentrations in four water samples from mine #1 ranged from 45 to 10,400 ng/L (nanograms per liter) in unfiltered water samples and from 7 to 225 ng/L in filtered water samples. Methyl mercury concentrations ranged from 0.01 to 1.0 ng/L in unfiltered samples. A single sample from mine #2 had 44.7 ng/L unfiltered and 7.4 ng/L filtered total mercury. Unfiltered methyl mercury was 0.01 ng/L in the single sample from mine #2. Limited monitoring data for mine-drainage flows from mine #1 measured with a Parshall measuring flume in April and May 1998 indicated discharge in excess of 50 gallons per minute (R. Humphreys, California State Water Resources Control Board, written commun., 1998)

Mercury in sluice box sediment

Total mercury in sediment samples collected from a sluice box in the Dutch Flat mining district ranged from 1,800 to 15,000 ng/g (nanograms per gram) wet basis, and from 2,400 to 21,000 ng/g dry basis. Methyl mercury in sediment ranged from 0.1 to 0.2 ng/g wet basis, and from 0.2 to 0.3 ng/g dry basis. A sample of white clay precipitate and fine sand from another processing site in the district had 4,270 ng/g wet and 6,710 ng/g dry weight total mercury. Methyl mercury was 0.003 ng/g wet weight and 0.005 ng/g dry weight. Total mercury recovered from panning of sluice box sediment ranged from 0.6 to 26 g/kg. Total mercury concentrations of 0.6, 0.9, and 1.0 g/kg were recovered from top gravels. Total mercury values for the bottom gravels were 16, 18, and 26 g/kg, indicating that the elemental mercury is strongly concentrated near the bedrock contact.

On the basis of observations in the Dutch Flat mining district, a preliminary estimate was made of total mercury in sluice-box sediments. A typical sluice-box has a cross sectional area of 15 ft^2 (5 ft wide and 3 ft high). Assuming that bottom gravels represent about 10 percent of the total sluice-box sediment, and using mercury concentrations for bottom and top sediments determined by panning, each linear foot of sluice box is estimated to contain 3 to 5 lb of mercury. This estimate pertains only to sluice boxes that remain full of sediment.

Ground and tunnel sluice boxes range in length from tens to thousands of feet. Therefore, sluice boxes are likely to contain hundreds to thousands of pounds of mercury in their present condition.

Mercury in fish tissue

The fish collected for mercury analyses were five adult rainbow trout (*Salmo gairdneri*). Total mercury in the fish tissue ranged from 0.1 to 0.2 µg/g (micrograms per gram) on a dry weight basis, or 0.03 to 0.05 µg/g on a wet weight basis.

DISCUSSION

Previous studies identified elevated levels of mercury in the aquatic food web of the Bear River watershed (Larry Walker Associates, 1997), however, identification of point source(s) were lacking. The mercury bioaccumulation problem is pervasive and regional throughout Sierra Nevada streams that are tributary to the Sacramento River, the Sacramento–San Joaquin Delta, and San Francisco Bay (fig. 4). This study has shown a relationship between the intensity of hydraulic gold-mining and degree of mercury bioaccumulation on a watershed scale (Fig. 5). Since the cessation of hydraulic mining, accumulated sediment from hydraulic placer mining has been transported to Sacramento–San Joaquin Delta and San Francisco Bay by sustained remobilization (James,1991). The USGS is working with the Forest Service, the Bureau of Land Management, and the Nevada County Resource Conservation District to develop plans to address mercury occurrence, fate, and transport in the Bear River and South Fork Yuba River watersheds, the areas of the Sierra Nevada that apparently are most environmentally impacted by hydraulic mining (fig. 5).

The extremely high mercury concentrations found in this study in water and sediment suggest that hydraulic placer-gold-mining sluices and drainage tunnels may be important contributors of mercury to the downstream Bay-Delta system and that remobilization of mercury is occurring at specific hot spots on a seasonal basis. Two important conclusions of this paper are that localized point sources of mercury likely exist throughout the entire hydraulic gold mining region, and that methylation of mercury is occuring close to the sources, allowing methyl mercury to enter the food web. These point sources offer the most treatable target areas for investigation of possible remediation projects.

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