High Levels of Mercury Contamination in Multiple Media of the Carson River Drainage Basin of Nevada: Implications for Risk Assessment

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Approximately 5.5×10^9 g (4.0×10^5 l) of mercury was discharged into the Carson River Drainage Basin of west-central Nevada during processing of the gold- and silver-rich Comstock ore in the late 1800s. For the past 13 decades, mercury has been redistributed throughout 500 km^2 of the basin, and concentrations are some of the highest reported values in North America. This article documents the concentration of mercury in the air, water, and substrate at both contaminated and noncontaminated sites within the basin and discusses the implications for risk assessment. At contaminated areas, the range of mercury concentrations are as follows: mill tailings, 3–1610 µg/g; unfiltered reservoir water, 53–591 ng/l; atmospheric vapor, 2–294 ng/m^3. These values are three to five orders of magnitude greater than natural background. In all media at contaminated sites, concentrations are spatially variable, and air and water mercury concentrations vary temporally. The study area is situated in a natural mercuriferous belt, and regional background mercury concentrations in all environmental media are higher than values typically cited for natural background. As a mercury-contaminated site in North America, the Carson River Drainage Basin is unusual for a number of reasons, including its location in a natural mercuriferous belt, high and sustained levels of anthropogenic mercury inputs, long exposure time, aridity of the climate, and the riparian setting in an arid landscape, where biological activity is concentrated in the same areas that contain high levels of mercury in multiple media.
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The various chemical forms of mercury [e.g., volatile species: elemental mercury (Hg^o), dimethyl mercury [$(CH_3)_2Hg$]; reactive species: divalent mercury (Hg^{2+}), mercury chloride ($HgCl_2$); and nonreactive species: methylmercuric chloride (CH_3HgCl), methylmercury (CH_3Hg)(*1*)] have intrinsic toxic properties that render them harmful to humans (*2*). Of greatest concern are the organomercury species, which are lipophilic and bioaccumulate in the food chain (*3*). The best-documented cases of mercury affecting human health occurred at Minamata and Niigata in Japan (*4*) and in Iraq (*5*). In most cases the predominant exposure pathway for humans is consumption of fish containing elevated mercury levels. Concern for exposure via fish consumption is reflected in the U.S. Food and Drug Administration action level for mercury in fish of 1 µg/g wet weight (3.6 µg/g dry weight) (*6*) and lower health advisory guidelines for some states (*7*). The concern over mercury in the environment has magnified in recent years as a result of increased mercury concentrations in lakes in remote areas of North America over the past century (*8*). The data indicate that the three- to fourfold mercury increment in these areas during the last 100–150 years comes from the atmosphere via wet and dry deposition (*1,9*).

Understanding the transport, transformation, and fate of mercury in the environment is critical, given the element's potential for methylation and subsequent biomagnification in the food chain (*3,10*). Unfortunately, measuring trace levels of mercury is complicated by the fact that it is ubiquitous in nature, and ultraclean sampling and analytical protocols are required to prevent inadvertent contamination (*1*). Accordingly, many features of mercury transport, fate, food chain contamination, and effects on the biosphere are better addressed in areas such as the Carson River Drainage Basin (CRDB) where mercury contamination is high and the duration of exposure is long. The duration of exposure is important because biomagnification is time dependent, and long exposures are likely to result in mercury-specific responses in sensitive organisms (*3*). These responses include accommodation at the physiologic or biochemical level, genetic adaptation at the population level, and behavioral avoidance mechanisms at the species level (*3*).

The Carson River Superfund Site was placed on the National Priorities List by the U.S. Environmental Protection Agency in August 1990 because of elevated mercury levels. The contamination is a legacy of processing the gold- and silver-rich Comstock ores mined from the Virginia Range between 1860 and 1890 (*11*) (Fig. 1). The Carson River site encompasses roughly 1200 km^2 within the CRDB.

Amalgamation with mercury was the most common method used to extract the silver and gold from the Comstock ore. Approximately 75 mills for ore processing were located in Six Mile, Seven Mile, and Gold canyons, and along the Carson River (*11*) (Fig. 1). For every 1000 kg of ore milled, 0.75 kg mercury was not recovered; as a result the mercury addition to the CRDB was approximately 5.5×10^9 g (*11*).

During the 30 years of intense ore milling in the Comstock Mining District, the Carson River terminated in what is now Stillwater National Wildlife Refuge and Carson Lake (Fig. 1). A public health warning has been issued for consumption of ducks from the Stillwater Wildlife Refuge based on the mercury concentration in duck muscle tissue (*6*). Since the completion of Lahontan Dam in 1915, the Carson River has filled Lahontan Reservoir. Cooper et al. (*12*) found some fish from Lahontan Reservoir exceeded the federal action level for mercury, and the highest reported concentration for the CRDB was 5.5 µg/g (*6*).

Preliminary data from the CRDB indicate that elevated mercury levels exist in soils, water, and biota as a result of redistribution of mercury during the 13 decades since mining activities began. To evaluate the extent of mercury redistribution, background levels of mercury must be established because the CRDB is located in one of three global mercuriferous belts (*13*). Mercury enrichment in the area is demonstrated by the presence of the Castle Peak Mine, which produced 8.5×10^7 g mercury in the early 1900s (*14*).

The goal of this article is to document mercury contamination in multiple media in the CRDB. The specific objectives are to 1) document mercury contamination in the geosphere, hydrosphere, and atmosphere within the CRDB; 2) document regional background mercury concentrations in the geosphere, hydrosphere, and atmosphere outside the area of contamination but within the mercuriferous belt; 3) document the concentrations of total mercury and methyl mercury (CH_3Hg) in surface waters of the CRDB; 4) compare the mercury levels in multiple media in contaminated and uncontaminated areas in western Nevada with other sites in North America; and 5) discuss the risks to humans and other organisms in the CRDB.

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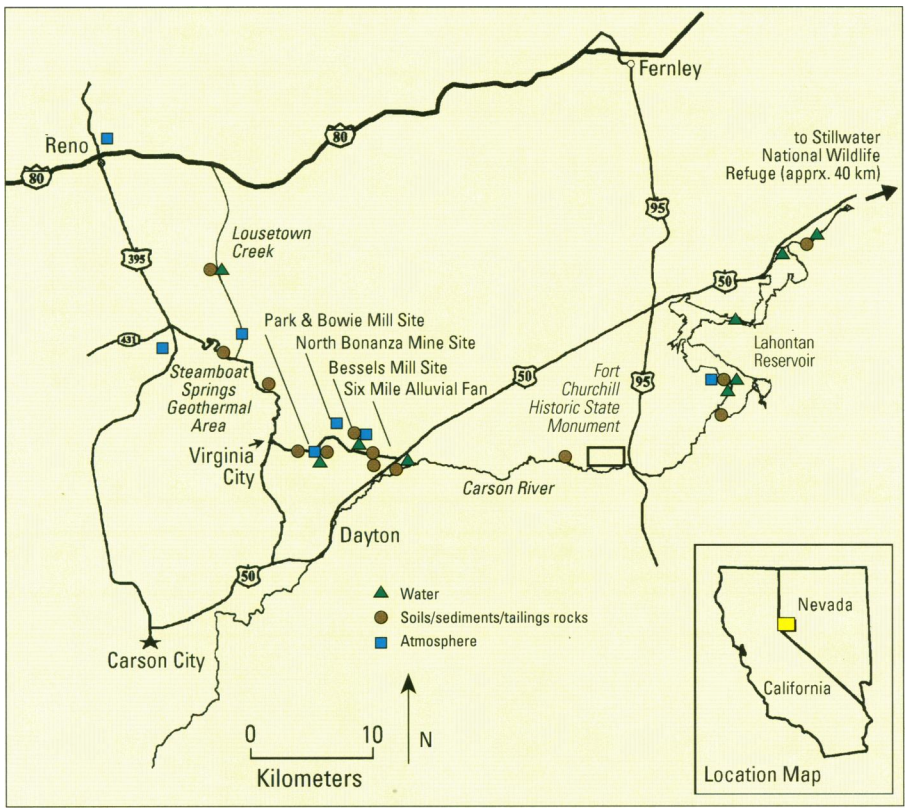

Figure 1. Map showing the location of the study area and atmosphere, water, and substrate sample locations. The Carson River Superfund Site extends from Virginia City to Dayton, along the Carson River floodplain to the Stillwater National Wildlife Refuge.

Methods

To characterize contaminated areas in the CRDB, we collected samples of substrate, water, and atmosphere from the Virginia City area and in Six Mile Canyon (located in the Virginia Range), from the alluvial fan leaving Six Mile Canyon, and adjacent to and within the Carson River and Lahontan Reservoir (Fig. 1). To characterize regional background mercury levels, we obtained samples from locations analogous to the CRDB but outside of the basin from Desert Research Institute (DRI), Steamboat Springs Geothermal Area, and the Lousetown Creek Drainage Basin (Fig. 1).

Substrate samples included fluvial, alluvial, and lacustrine sediments (n = 23), soils (n = 8), mill tailings (n = 38), and rock samples (n = 4). We used homogeneous samples of 15 cm depth to determine mercury concentrations in 49 substrate samples. Twenty samples were taken at specific stratigraphic intervals to characterize vertical mercury distribution. Reconnaissance sampling was done for background soils, sediments, and rocks. To assess mercury concentration at contaminated sites, detailed sampling was done at two mill sites, and reconnaissance sampling was done of representative stratigraphic units.

Ten grams of sample were digested in 15 ml agua regia, and the resulting solutions was analyzed for mercury using a Buck Scientific hydride cold-vapor generation system attached to a Perkin Elmer 2380 atomic absorption spectrophotometer at the Nevada Bureau of Mines and Geology (Reno, Nevada). The accuracy for the analysis of geologic samples, based on comparison with five U.S. Geological Survey Geochemical Exploration standard reference samples and one NIST standard, was ±19%. The analytical precision was 21%, based on replicate samples of a Bureau of Mines standard. The limit of detection was 10 ppb (Desilets M, Nevada Bureau of Mines, personal communication).

We collected surface water samples from Lahontan Reservoir (n = 6), Six Mile Creek (n = 2), and Lousetown Creek (n = 2) during August and September of 1993 (Fig. 1) to assess mercury concentration in waters of the CRDB. Mercury concentrations in Lousetown Creek waters were selected to represent regional background; the geologic landscape is similar to that hosting contaminated sites along Six Mile Canyon.

Unfiltered surface water samples were collected in acid-washed Teflon bottles (*15*) and analyzed by Brooks Rand, Ltd., (Seattle, Washington). To determine total mercury concentrations in water, Brooks Rand used a bromine-chloride solution to oxidize the mercury (*16*) and reduced the mercuric ions to Hg° using tin chloride (*15*). Methyl mercury in water was concentrated by extraction with methylene chloride or distillation (*17*). Samples were purged onto gold-coated sand traps (*15*), and concentrations were measured using a cold-vapor atomic fluorescence spectrophotometer (CVAFS) single-stage system (*18*). Analytical precision based on replicate samples for total mercury and CH_3Hg was less than 9% and 11%, respectively; purge blanks were ±5 ng/l for total mercury and ±0.3 ng/l for CH_3Hg; accuracy based on analysis of NIST reference materials was ±12%. The limit of detection was 20 pg/l or parts per trillion (Spurling D, personal communication).

We took 39 atmospheric samples at 8 different locations (Fig. 1). At two of the three sample sites in Six Mile Canyon, data were collected over mill tailings. We chose five locations to characterize regional background, one of which was the geothermally active Steamboat Springs area, documented as being naturally enriched in mercury (*19*).

We collected atmospheric samples by amalgamating total mercury on traps consisting of a glass tube filled with gold-coated quartz sand (*20,21*). The sampling train, connected with acid-washed Teflon tubing, included a 2-µm Teflon in-line filter followed by a gold trap and a Tylan General flow controller (*22*). Flow controllers were calibrated with a bubble-flow meter and found to have a systematic flow error due to altitude, for which the data were corrected (*23*). Air was pulled through the sample trap at a rate of either 1.1 or 2.2×10^{-5} m^3/sec (0.65 or 1.32 l/min). Three replicate sampling trains were set up one meter above the ground. Using this sampling technique and the CVAFS described below, total atmospheric mercury was measured with an average precision of 12.6% at atmosphere concentrations between 2 and 300 ng/m^3.

We measured concentrations of total mercury in the atmosphere using a nondispersive atomic fluorescence spectrometer (CVAFS) at the University of Nevada, Reno. The dual stage gold-amalgamation trap gas train system used to introduce mercury into the glass cell of the CVAFS was discussed by Fitzgerald and Gill (*20*). The linear working range for the CVAFS was 0.1–15 ng mercury. Analytical precision associated with replicate additions of headspace gas over a standard maintained at constant temperature was 1.2–1.5%. The standard consisted of 10 g Hg° in a 1-l

flask maintained at constant temperature in a Fisher Isotemp heating-cooling circulating water bath so that a gas-tight 100-µl syringe would collect a 1 ng sample per 100 µl of headspace gas. Data quality assurance and quality control was evaluated by sending splits from triplicate atmospheric samples and gold-coated sand traps injected with a known amount of mercury to Brooks Rand, Ltd. and Frontier Geosciences (Seattle, Washington). Both laboratories used the technique described above for calibrating their CVAFS. Based on sample splits, the mean sample error for the CVAFS system was 10.5%.

The data on mercury concentration in biota were not obtained as a part of this study because two other preliminary surveys documented mercury contamination in Lahontan Reservoir (*12*) and Stillwater National Wildlife Refuge (*6*). The inclusion of these data in the discussion is important for documentation of the magnitude of multimedia contamination in the CRDB.

Results and Discussion

Regional Background Concentrations of Mercury

Background mercury concentrations in sediments and soils from the Lousetown Creek Drainage Basin ranged from 0.1 to 1.6 µg/g (Table 1). The range of mercury concentrations in rock samples taken from the Lousetown Creek and Virginia City area was 0.02–0.03 µg/g (Fig. 1). Whitebread (*24*) reported mercury concentrations in rocks associated with the Comstock ore veins of 0.02–10 µg/g. This range of 0.02–10 µg/g for regional background mercury concentrations in substrate is higher than values normally cited as representative of global background (0.01–0.05 µg/g) (*25*).

Mercury concentrations in water samples from areas not affected by mining (Lousetown Creek) were 8 and 10 ng/l (Table 2). Methylmercury concentration for one of the samples was 0.43 ng/l, 4% of the total mercury. Total mercury concentrations in Lousetown Creek were higher than natural background values typically cited for freshwaters of 1–3 ng/l (*1,26*); this elevated mercury concentration in surface waters in the area is a consequence of the drainage basin containing mercury-enriched source rocks (*14*). A total mercury concentration of 3.0 ng/l was obtained for the Carson River above relict mill sites (Warwick et al., unpublished data), reflecting the lack of anthropogenic contamination and low mercury source rocks.

Average values for regional background atmospheric total mercury ranged from 1.8 to 6.0 ng/m^3. Mercury concentrations in the atmosphere from the Lousetown Creek catchment were 3.6 ± 0.1 ng/m^3 (mean ± SD) for October and 2.4 ± 0.3 ng/m^3 for January (Table 3). The highest regional background concentrations are from the Steamboat Springs geothermal area, where mercury was observed to collect on the brass armor of thermometers used to obtain temperatures of geothermal vents (*19*).

Mercury concentrations in the atmosphere of this western Nevada region are slightly greater than or equal to reported

Table 1. Total mercury concentration in contaminated and noncontaminated substrate of the Carson River and Lousetown Creek Drainage Basins

Sample type	*n*	Range (µg/g)	Mean ± SD
Background			
Lousetown Creek Sediment/soil	8	0.1–1.6	0.4 ± 0.5
Virginia Range Rock samples	4	0.02–0.03	0.02 ± 0.00
Contaminated sites			
Six Mile Canyon			
Flume deposits	4	2.9–5.0	3.0 ± 0.9
Park and Bowie Mill site	4	13–848	414 ± 297
Bessels Mill site	33	66–1610	600 ± 584
Six Mile Flat alluvium (*28*)	3	0.4–550	
Carson River Sediments	8	2–156	27 ± 54
Lahontan Reservoir Sediments	8	0.02–103	17 ± 32
Other studies			
Natural background (*24*)		0.01–0.05	
Clear Lake Superfund (*30*)		0.9–159	
Contaminated soils (Oak Ridge, TN) (*31*)		≤3000	

Table 2. Total mercury and methylmercury (ng/l) concentrations of unfiltered surface waters from the Carson River Drainage Basin and comparison with other studies of total mercury in water

	Total Hg	CH_3Hg	CH_3Hg (%)	Reference
Background				
Lousetown Creek	10	0.4	4.0	
	8[a]			
Contaminated sites				
Lahonton Reservoir	53	3.3	6.0	
	99	3.1	3.0	
	138	1.9	1.0	
	424	5.7	1.0	
	481	5.1	1.0	
	591	21	3.0	
Six Mile Canyon	3,880	9.4	0.2	
	35,400	7.2	0.02	
Other studies of total Hg in water				
Natural background	1–3			(*7*)
Carson River	3			(*27*)
Pyramid Lake, NV	2			(*15*)
Clear Lake Superfund site	5.5–69			(*30*)
Davis Creek Reservoir	5.36–6.59			(*15*)

[a]Data from David Wayne, personal communication (Los Alamos National Laboratories, New Mexico, August 1993).

Table 3. Total mercury concentration in the atmosphere (ng/m^3) from the Carson River Drainage Basin and uncontaminated sites in western Nevada

Location	Month	*n*	Range	Mean ± SD
Regional background				
Lousetown Creek	October	2	3.5–3.7	3.6 ± 0.1
	January	3	2.1–2.8	2.4 ± 0.3
Desert Research Institute	October	3	1.7–1.9	1.8 ± 0.7
	January	3	2.2–2.3	2.2 ± 0.05
Rancho San Rafael	October	1		3.50
Steamboat Springs	January	4	4.7–7.1	6.0 ± 0.9
Contaminated sites				
Bessels Mill	October	6	205–294	240 ± 27
	January	5	51.9–60.5	58.2 ± 3.2
Park and Bowie Mill	January	5	26.6–28.9	28.7 ± 0.9
North Bonanza	October	3	4.8–5.1	5.0 ± 0.1
	January	2	2.0–2.9	2.4 ± 0.5
Lahontan Reservoir	October	2	2.0–2.6	2.3 ± 0.3
Reported natural background (*7*)			1–4	

background concentrations of 1–4 ng/m^3 (*1*). As these atmospheric samples were taken during October and January, it is likely that atmospheric concentrations during warmer months will be higher, given the temperature dependence of mercury evasion documented by Lindberg et al. (*27*).

In summary, background concentrations of mercury in water and sediment for this western Nevada region were elevated by one to two orders of magnitude above reported natural background values, respectively. Regional background atmospheric concentrations of mercury were within and above the reported range for natural background levels (Fig. 2).

Concentrations of Mercury within the CRDB

Mercuriferous flume and mill tailing samples from contaminated sites in Six Mile Canyon exhibited nearly a three–order of magnitude range in mercury concentration from 2.9 to 1610 µg/g (Table 1). Mill sites showed a heterogenous distribution of mercury concentrations both horizontally and vertically. This is represented by the distribution of mercury concentrations at Bessels Mill, where surface mercury concentrations ranged from 66 to 1610 µg/g (Fig. 3), and the coefficient of variation exceeded 90%. Mercury concentrations at Bessels Mill also varied with depth, and in some cases differed by an order of magnitude within several centimeters (Fig. 3). There was no consistent pattern in the mercury concentration profiles with depth (Fig. 3).

Mill tailings, discarded as waste in Six Mile Canyon, have been eroded and transported out of the canyon and deposited on

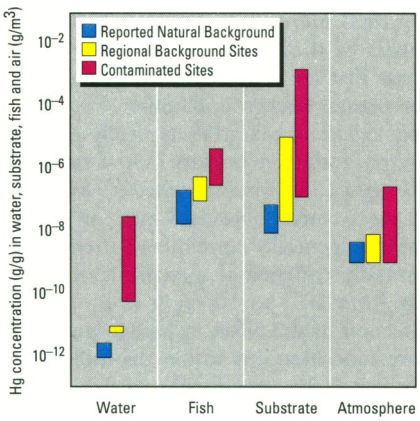

Figure 2. Graph illustrating the concentration of total mercury, in water, fish, substrate, and atmosphere from contaminated areas at the Carson River Superfund site in relationship to regional background and reported natural background concentrations. Natural background concentrations are from Andersson (*25*), Lindqvist et al. (*1*), and Huckabee et al. (*33*). Data for fish in the Carson River Drainage Basin are from Cooper (*12*) and Hoffman et al. (*6*).

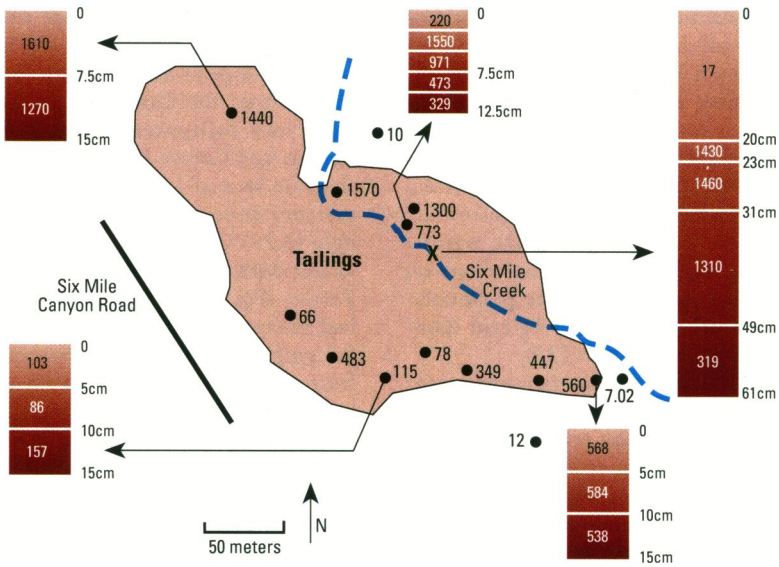

Figure 3. Map showing total mercury concentrations (µg/g) at the Bessels Mill site located within the Carson River Drainage Basin. The surface mercury concentrations represent a sample of 15 cm depth. Vertical variation at a single sample location is shown for five sites using stratigraphic columns.

an alluvial fan and in the Carson River during the last 13 decades. Mercury concentrations on the alluvial fan ranged from <1 to 550 µg/g (28). Mercury concentrations in sediments within and adjacent to the Carson River ranged from 1.9 to 156 µg/g. Total mercury concentrations in sediment samples from Lahontan Reservoir were 0.02–103 µg/g, with a coefficient of variation of 175% (Table 1).

These substrate mercury concentrations are some of the highest values reported in the literature and are notably high for North America. For example, reported values of total mercury in substrate at the Clear Lake Mercury Mine Superfund site in California ranged from 0.9 to 159 µg/g (*29*). Kim et al. (*30*) reported mercury concentrations up to 3000 µg/g for floodplain soils contaminated by nuclear weapons processing near Oak Ridge, Tennessee. Most of the mercury at the Oak Ridge site was mercury sulfide. Mercury species in substrate at contaminated sites in the CRDB have not been established. However, as the mercury introduced into the CRDB was elemental mercury and conditions are generally aerobic, most of the mercury in substrate is likely to be elemental or mercury chloride.

Total mercury concentrations in unfiltered surface waters of Lahontan Reservoir in August and September 1993 ranged from 53 to 591 ng/l ($\bar{x}$ = 297) (Table 2). Methylmercury concentrations ranged from 3.3 to 21 ng/l ($\bar{x}$ = 6.68) and averaged 2.3% of total mercury (Table 2). These are the highest unfiltered total mercury and CH_3Hg concentrations reported for North American surface waters (*15,29*). Unfiltered total mercury and CH_3Hg concentrations for the Clear Lake Site were 5.5–69 ng/l and 0.02–0.18 ng/l, respectively (*29*). Thus, the mercury concentration in water between the two sites differs by one to two orders of magnitude.

Within Lahontan Reservoir, total mercury concentrations were lowest near Lahontan Dam (53 and 99 ng/l), where the Truckee Canal brings water from the Truckee River into the reservoir (Fig. 4). Concentrations increased with proximity to the mouth of the Carson River (481 and 591 ng/l). Methylmercury concentrations for the reservoir were less variable than that of total mercury; however, distribution was similar to that of total mercury (Fig. 4). Methylmercury constituted a higher percentage of the total mercury concentration near Lahontan Dam (Table 2). Mercury concentrations in Lahontan Reservoir were two orders of magnitude greater than its analog Pyramid Lake (2 ng/l), located in a desert basin north of Reno and unaffected by mining inputs (*15*).

Water samples collected from Six Mile Canyon adjacent to areas with highly contaminated tailings had extremely high total mercury concentrations (3800 and 35400 ng/l). Methylmercury values from the same samples were 9.4 and 7.23 ng/l, representing less than 0.2% of total mercury (Table 2).

Total atmospheric mercury concentrations at the Bessels Mill Site (substrate mercury concentrations of 7–1610 µg/g) were 240 ± 27 ng/m3 ($\bar{x}$ ± SD) for October and 58.2 ± 3.2 ng/m3 for January (Table 3). At the Park and Bowie Mill site (substrate concentrations of 13–848 µg/g), atmospheric mercury concentrations in January were 28.7 ± 0.9 ng/m^3. Atmospheric mercury concentrations at the

North Bonanza site, not directly associated with contaminated tailings but within Six Mile Canyon, averaged 5.0 ± 0.1 ng/m^3 for October and 2.4 ± 0.5 ng/m^3 for January. Atmosphere samples from the Lahontan Reservoir area in October had an average total mercury concentration of 2.3 ng/m^3. Values in the same location are expected to be higher during the warmer months, given the temperature effects on mercury evasion (*27*) and the preponderance of diurnal inversions in arid landscapes during the summer (*31*).

Atmospheric mercury concentrations measured over contaminated sites in the CRDB are the highest reported values in North America. Kim et al. (*30*) reported atmospheric mercury concentrations of 6.4 ng/m^3 over a site contaminated with primarily mercury sulfide near Oak Ridge, Tennessee.

Concentration of Mercury in Biota of the CRDB

Although the data are limited to general surveys, they demonstrate that mercury contamination of the landscape within the CRDB has resulted in elevated mercury concentrations in the biosphere. Some fish species from the Carson River, Lahontan Reservoir, Stillwater National Wildlife Refuge, and Carson Lake exceed the federal action level of 1.0 µg/g wet weight, with mercury concentrations approaching 5.5 µg/g (*6,12*) (Fig. 2). Fish from the Fernley Water Management Area (FWMA), near Fernley (Fig. 1) and outside of the CRDB, had mercury concentrations not exceeding 0.5 µg/g (*6*). Fish mercury concentrations from the FWMA were used to represent background for western regional Nevada. The mercury concentrations in fish from the FWMA were somewhat higher than the natural background level in fish estimated by Huckabee et al. (*32*) as ranging from 0.02 to 0.2 µg/g.

Hoffman et al. (*6*) reported mercury concentrations of 0.43–2.40 µg/g dry weight for 12 of 102 plant samples from Carson Lake and Stillwater National Wildlife Refuge. They concluded that these concentrations warranted concern based on the research of Heinz (*33*), who found that mallards maintained on a diet containing 0.39 µg/g CH3Hg, exhibited adverse reproductive effects. Mercury concentrations in similar plant types from the uncontaminated FWMA were less than 0.6 µg/g. Mercury concentrations in *Hemiptera sp.* (true bugs) and *Diptera sp.* (two-winged flies) from Carson Lake wetlands and Stillwater Refuge ranged from 0.3 to 5.4 µg/g (*6*). Insects of the same genus from the FWMA had mercury concentrations ≤0.4 µg/g (*6*). These data indicate that mercury in the CRDB has led to higher-than-regional background mercury concentrations in biota of the CRDB and that the increase above background ranges from 40 to 100%.

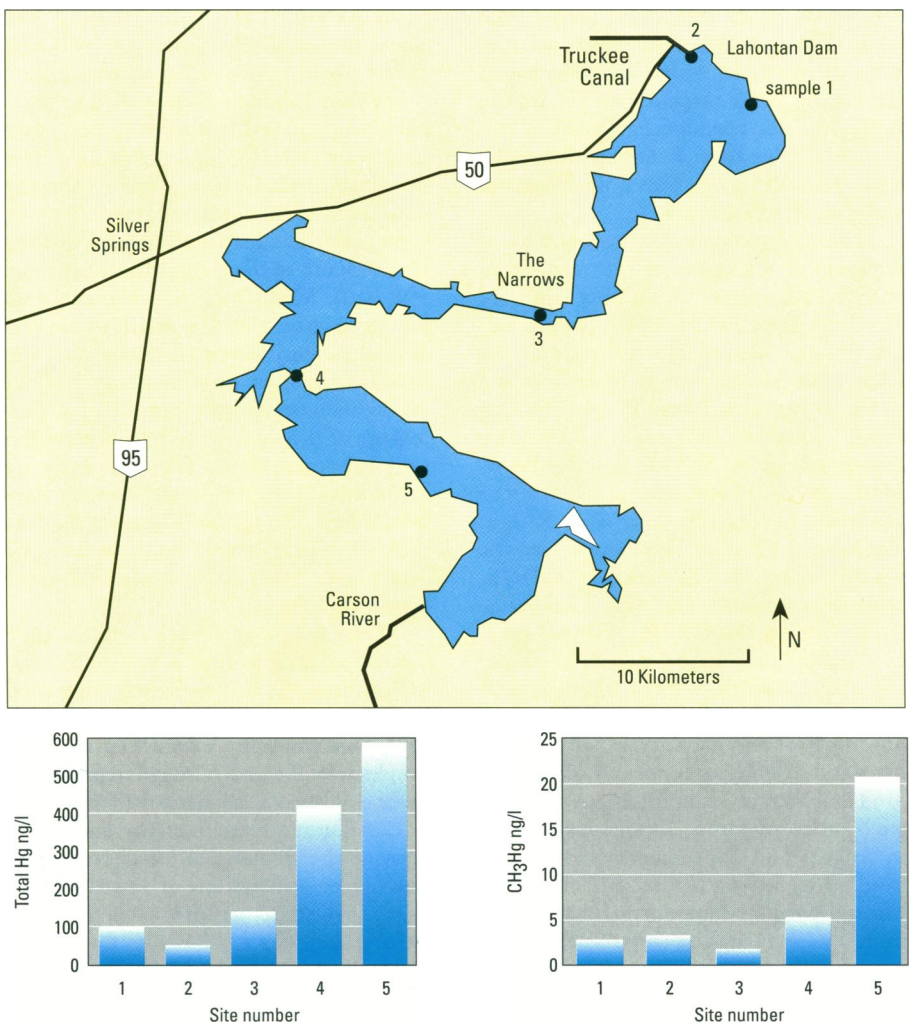

Figure 4. Variation in total mercury and CH_3Hg concentrations (ng/l) in unfiltered surface water samples from Lahontan Reservoir.

Uniqueness of Mercury Contamination in the CRDB

There are a number of unusual features regarding the mercury contamination in the CRDB. The first and most prominent is the high levels of mercury in multiple media (Fig. 2). The concentrations in substrate materials, atmosphere, and water for both inorganic and organic mercury are among some of the highest reported concentrations at the regional, continental, and global scale. While the concentrations vary spatially and temporally within contaminated landscapes, the values are one to three orders of magnitude higher than the average natural background values reported in the literature, and this pattern is consistent among all media (Fig. 2).

The second feature is the fact that the CRDB lies in a mercuriferous belt that extends down the western coast of North America and into South America (*13*). The data presented here indicate that regional mercury concentrations in all media of the CRDB are elevated above those that are normally cited as the range for natural background values. For example, substrate materials typically contain mercury concentrations in the range of 10^{-7} g/g (*25*), whereas substrate materials in west-central Nevada outside of the anthropogenically contaminated region are naturally enriched at mercury levels ranging from 10^{-7} to 10^{-5} g/g (Fig. 2). The direction of the offset in background mercury concentrations within the mercuriferous belt is the same for the surface waters, biota, and the atmosphere (Fig. 2). The evidence demonstrating the magnitude of natural mercury enrichment in this region is important because the baseline for addressing human health and ecological risk is likely to be higher in sites situated within the mercuriferous belt.

The third feature is the size of the area within the CRDB that is contaminated. The total linear dimension of the contami-

nated water course extending from the mill tailings in Six Mile Canyon to Stillwater National Wildlife Refuge approaches 100 km, and the contaminated surface area due to eolian and fluvial transport is likely to approach 500 km^2. Although the surface area that is contaminated is not unprecedented, the size is unusual relative to other mercury-contaminated sites in North America.

The fourth feature is the aridity of the climate, which has several consequences. Unlike areas that are more mesic, atmospheric deposition of mercury via wet and dry process is negligible. In many other areas, atmospheric deposition is the dominant or sole source of mercury input to catchments (*34*), and quantifying this input is difficult (*22*). In addition, the low levels of rain in Nevada limit the size and vigor of the plant communities (*31*), thereby reducing sites for dry deposition of mercury plant canopies are one of the principal sites for gas-phase deposition (*35*). The aridity also facilitates the evasion of mercury; from the landscape because the exchange of latent heat between the atmosphere and the continental landscape is greater in the CRDB than in more mesic environments. The issue of temperature is particularly important, for flux has been shown to be temperature dependent (*27*), and the daily amplitude for air temperature in the summer in the Great Basin is typically 20–25°C (*31*).

The fifth feature is a consequence of the hydrogeochemistry of the CRDB. The pH of Lahontan reservoir surface waters is alkaline, ranging from pH 7.3 to 8.7. Most studies have shown an inverse relationship between pH and mercury bioavailability (*37*). Yet the concentrations of mercury in fish and insects in the CRDB are among some of the highest reported values in North America. In addition, the CRDB has elevated levels of selenium, principally due to evapo-concentration (*38*), and selenium is an antagonist to mercury uptake and/or mammalian toxicity (*3*).

The final feature is the issue of risk assessment for human health and ecology. The framework for addressing at-risk populations places a premium on understanding the pathways of mercury exposure and measuring specific rates of contaminant transport to receptors. It is widely assumed that the principal pathway for mercury exposure in humans is food consumption, and this feature is embodied in the action guidelines developed at the state (*6,7*), federal, and international level based on mercury levels in fish (*1*). In the case of the CRDB, the pathways by which humans are exposed to mercury is likely to be more complex, extending to inhalation, dermal contact, and ingestion of contaminated water. Each single pathway for mercury exposure may be individually low but significant in contributing to the total body burden of mercury.

This concern for multiple exposure pathways for mercury in the CRDB is also appropriate for ecological risk assessment, and we propose that there is a far greater probability of biological effects occurring in nonhuman versus human species in both terrestrial and aquatic environments within the CRDB. The level of contamination in fish, insects, and aquatic macrophytes is high (*6*), and the data indicate that at least some individuals have body burdens of mercury above the thresholds for effects (*3*). The fact that the CRDB is a riparian landscape in an otherwise arid environment means that the feeding and nesting behavior of many species is confined to the water course, thereby increasing the probability of mercury exposure. In addition, because mercury concentrations have been elevated for many decades, at-risk species and populations may have already responded to the mercury contamination via behavioral modifications, physiological or biochemical accommodations, or genetic shifts in the frequency of alleles that confer mercury resistance.

To identify at-risk species within the CRDB, the probability of finding deleterious effects due to mercury contamination is more likely in nonhuman species, including birds, insects, fish and microbes. This is a consequence of several factors but largely reflects the distinctive nature of the CRDB riparian and wetland environment, which focuses biological activity in areas that have contained very high levels of mercury for many decades.

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