

The Hg geochemistry of a geothermal stream, Steamboat Creek, Nevada: natural vs. anthropogenic influences

W. B. Lyons · D. M. Wayne · J. J. Warwick · G. A. Doyle

Abstract A series of water samples from Steamboat Creek, Nevada, was analyzed for total mercury concentrations. Concentrations from these waters were 40 to 60 times higher than the pristine mountain streams entering the creek. The major source of the mercury entering Steamboat Creek is probably from gold/silver processing that took place in the 1860s.

Key words Mercury · Gold mining · Steamboat Creek, Nevada

Introduction

The knowledge of the biogeochemical dynamics of mercury (Hg) and its behavior at the surface of the Earth is of great interest due to the toxicity of the element even at very low concentrations. This is particularly true of the methylated forms (Fitzgerald and Clarkson 1991). Globally, both natural and anthropogenic activities contribute Hg to the surficial environment (Nriagu 1989; Mason and others 1994). Fitzgerald (1979) has pointed out that the assessment of Hg in the environment requires accurate and precise data in order that reliable identification of major transfer routes of the element be determined and then modeled. In 1992, University of Nevada, Reno, De-

sert Research Institute scientists initiated a study of the Carson River-Lahontan Reservoir System (CRLRS). This region was designated to the National Priority List of Superfund Sites in August 1990 because of elevated mercury levels. This mercury is believed to have originated from the processing of gold and silver from the nearby Comstock Lode during the 1860s to 1890s. It has been estimated that 5.5×10^6 kg of Hg was introduced into the environment during this 30-year period (Smith 1961). During the, subsequent ~100 to 130 years, a portion of this Hg has been redistributed both via runoff from tailings pile and subsequent riverine transport (Miller and others 1995) and via the atmosphere from volatilization (Gustin and others 1996).

In addition to the importance of anthropogenically introduced Hg into this region, the area is a known mercuriferous belt with abnormally high natural background levels of Hg in fish, sediment, and water compared to non-mercuriferous belt regions (Gustin and others 1994). Steamboat Creek, Nevada ($39^{\circ}22'40''\text{N}$, $119^{\circ}44'33''\text{W}$) is a relatively small watershed of $\approx 320 \text{ km}^2$ (Fig. 1). Steamboat Creek offers a unique location in order to assess the influence of both natural and anthropogenic processes on the contribution of Hg into an aquatic system on a local scale, as the potential exists for Hg input from both sources. From 1859 to 1890, approximately 5.5×10^6 kg of metallic Hg was released in the Virginia City region (Fig. 1) as a result of refining the Comstock Lode gold and silver ores (Smith 1961). Although the vast majority of this "lost" Hg was discharged into the Carson River drainage to the south and east of Virginia City, historical information suggests that a portion of the earliest mined ore was processed on the shores of Washoe Lake (Ansari 1989). Steamboat Creek drains Washoe Lake, flowing N-NE and finally intersecting the Truckee River, east of Reno, NV (Fig. 1).

Historical documents indicate that in the early 1860s there were at least six mills reducing Comstock ore in Washoe Valley (Ansari 1989). During these earliest days of the Comstock mining, the Ophir Mill was located near Washoe City (Fig. 1) and in 1862 processed as much as 4.5×10^4 kg of ore per day. Due to the difficulty of transport of both ore down and timber up the steep grade from Virginia City to Washoe City, especially in winter, the sites of extensive milling began to change to Carson River (to the south and east of Virginia City) locations by the mid-1860s (Ansari 1989). The Ophir Mill (on Washoe

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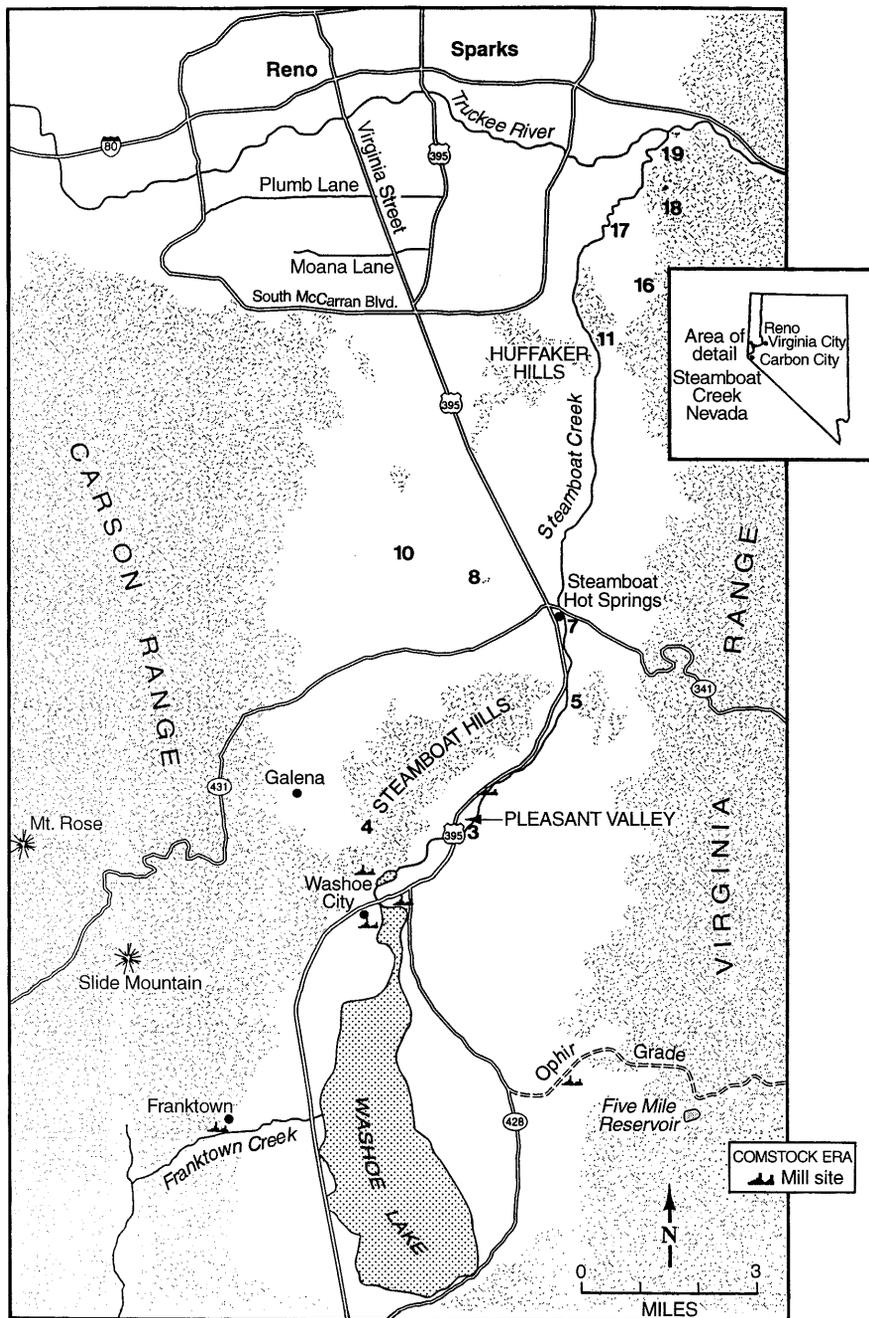


Fig. 1
Steamboat Creek drainage, Nev

Lake) was closed by 1866. Other small mills operated on and off into the 1870s and one mill even existed north of Washoe Lake at the lower end of Pleasant Valley until 1870 (Ansari 1989). It was reported to have a large water wheel, and perhaps its operations were in direct contact with Steamboat Creek. Inflow of Hg-laden debris during and after milling operations could have taken place at the northern most end of Washoe Lake or Little Washoe Lake and later have been transported northward by Steamboat Creek (Fig. 1).

The Steamboat Springs geothermal area also drains directly into Steamboat Creek, north of Washoe Valley and Washoe Lake (Fig. 2). Steamboat Springs is presently an

active equivalent of an epithermal gold-silver ore forming system, discharging thermal waters and gases in an area $\sim 5 \text{ km}^2$ (White 1968). Hg concentrations as high as $200 \mu\text{g g}^{-1}$ have been observed in siliceous muds deposited from the springs (Silberman and others 1979). Hydrothermal systems, in general, can discharge large amounts of Hg to the surface of the Earth (Christensen and others 1983; Peters 1991). Therefore, Steamboat Springs is a likely source of "natural" Hg input into Steamboat Creek. In addition to these potentially important sources of Hg to Steamboat Creek, a region to the east of the creek, close to the drainage divide, is a site of former Hg mining. This area, known as the Castle Peak mine, is located

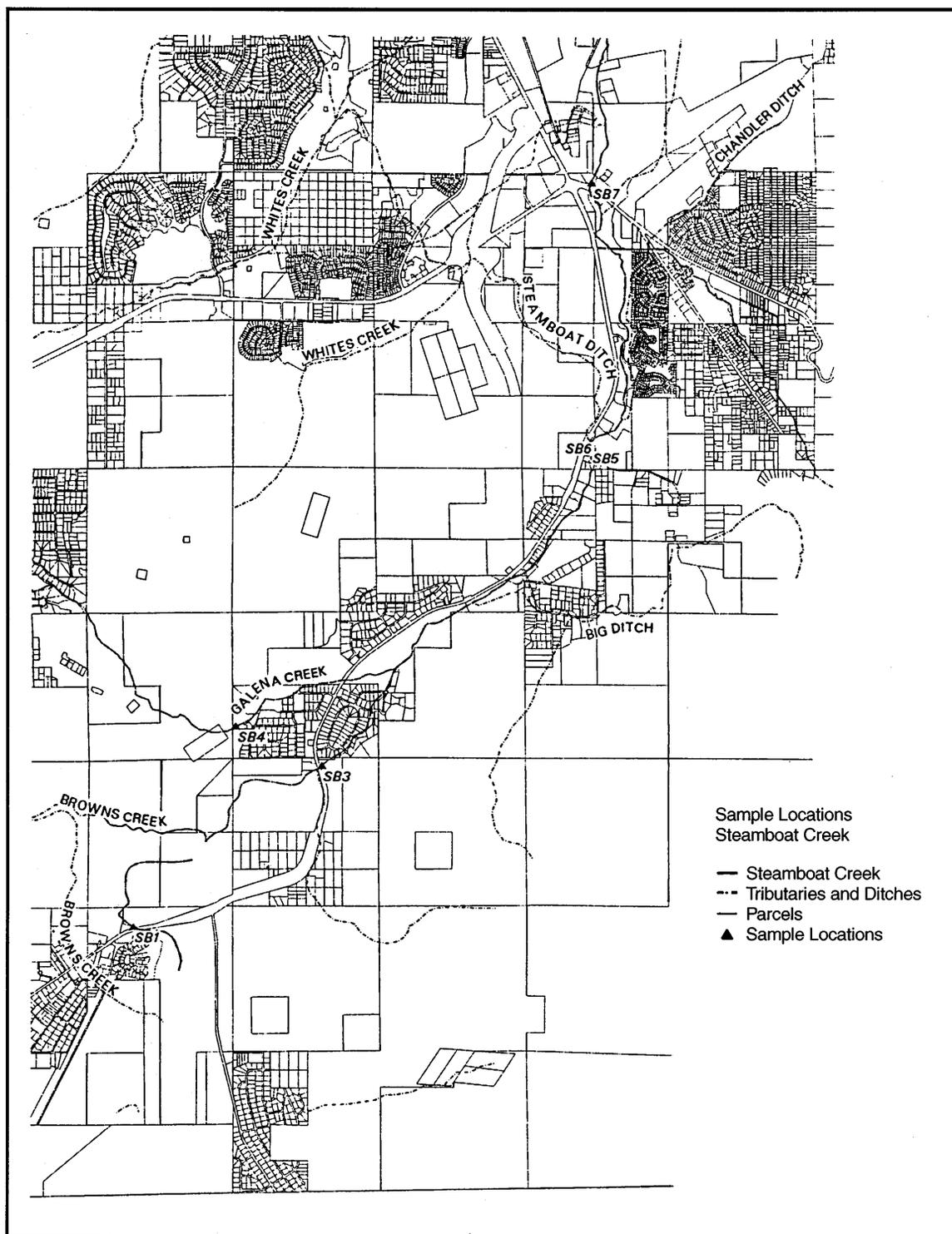


Fig. 2
Southern portion of Steamboat Creek, Nev, with sampling sites SB1-SB7

~17 km north of Virginia City on the northwest side of Castle Peak at ~1760 m in elevation. Approximately 2600 flasks of Hg were mined from this prospect from 1927 until 1943 (Whitebread 1976). Although much of this area probably drains to the east and north into the west fork of Lousetown Creek and then into the Truckee River east of Steamboat Creek, there is some potential for possible flow into the Steamboat Creek drainage, and again sug-

gests a potential for a larger than normal background contribution of Hg.

The purpose of this work was to establish, using ultra-clean collection and laboratory techniques, the total Hg (Hg_T) concentrations in the waters of Steamboat Creek, and then to attempt to evaluate the source of the Hg to these waters. The aim of this research was to determine whether the past mining and refining activities, or the

naturally occurring thermal water input have effected the Hg concentrations in Steamboat Creek. The last objective of the work was to determine what quantitative impact Steamboat Creek Hg input has on the Truckee River.

Methods

In April 1993, seven samples from Steamboat Creek proper were collected, three samples from mountain streams that feed the creek from the Sierra Nevada (i.e., from the west), and three samples from irrigation/drainage ditches flowing into the creek. Sampling was done in cooperation with the Nevada Department of Environmental Protection (NDEP). Although many geochemical investigations of Hg have been conducted over the past thirty years or so, many of the data on natural waters are unreliable, due, in part, to contamination through sample collection, storage, and analysis (Fitzgerald 1979; Gill and Fitzgerald 1985; Gill and Bruland 1990). Mercury samples were collected by immersing precleaned 0.5 or 1-l Teflon bottles directly into the water. Care was taken not to sample the surface microlayer, or to contaminate the sample with bottom sediment. The sample bottles were inverted, submerged, uncapped underwater, filled completely, capped, and double-bagged in precleaned polyethylene bags. Elbow-length plastic gloves were worn during sample collection to minimize contamination. All samples were acidified within 24 h of collection with Optima HCl to pH < 2 and refrigerated at 4 °C until analysis (Wayne and others 1996). Samples were not filtered, and therefore the data are presented as total Hg (Hg_T) or that Hg in the water which is in the dissolved and colloidal forms, as well as that Hg which is desorbed from particulate material at pH of < 2.

All samples were analyzed in a clean laboratory environment. Details are reported elsewhere (Wayne and others 1996) and will not be repeated in great detail here. Analyses were performed on 25–225-ml aliquots using NaOH-NaBH₄ reduction (Gill and Bruland 1990), gas-phase sparging with Hg-free, high-purity N₂ and trapping onto Au-coated quartz sand (Gill and Fitzgerald 1987). The trapped Hg was then thermally stripped from the traps and quantified by cold-vapor atomic fluorescence spectroscopy (CVAFS) (Gill and Fitzgerald 1985). Purge blanks were 0.1–0.3 ng and detection limits were 0.08 ng. Contamination from the Teflon sample bottles was below our detection limit. The Hg data are presented in Table 1. Most of the Hg samples were analyzed in triplicate or duplicate. One sample (White's Creek) was taken in duplicate; and the contents of each bottle analyzed in triplicate.

The NDEP also collected water samples at the same locations as part of their long-term aquatic monitoring program. Some of their data are also presented in Table 2. These data (Cl⁻ and dissolved As) will be utilized to help elucidate the source of Hg in the Steamboat Creek system.

Table 1

Total mercury (Hg_T) concentrations in Steamboat Creek and tributaries. Samples collected 13 April 1993. Values in ng l⁻¹ [* Steamboat Creek proper, ND=no data, ° previously reported in Wayne and others (1996), + only one analysis, ‡ only duplicate analysis, all other – triplicate analysis, ●● agricultural “ditches”, ** “pristine” mountain streams]

sample no.	sample name	value
SB 1	Little Washoe Lake Outfall*	ND
SB 3	Pleasant Valley*	51 ± 8‡
SB 4	Galena Creek [°] **	1.6 ± <0.1
SB 5	Rhodes Road*	25 ± 2
SB 7	Geiger Grade*	24 ± 1
SB 8	Whites Creek [°] **	1.2 ± 0.4, 1.25 ± 0.11
SB 10	Thomas Creek [°] **	1.1 ± 0.1
SB 11	Short Lane*/Pit Outflow	74 ± 2
SB 12	Alexander Ditch●●	ND
SB 14	Rio Poco	ND
SB 16	Boynton Slough●●	2.0 ± 0.1
SB 17	Pembrook*	82 +
SB 18	York Ditch●●	2.7 ± 0.4
SB 19	Clear Water Way*	84 ± 2

Results

The concentration of Hg_T in Steamboat Creek varies from 24 to 84 ng l⁻¹, while concentrations in the agricultural ditches range from 2.0 to 2.7 ng l⁻¹ and the pristine mountain streams have values ~1–2 ng l⁻¹ (Table 1). The modern-day average Hg_T is thought to be 5 ng l⁻¹, while the preindustrial riverine value was probably closer to ~1.5 ng l⁻¹ (Mason and others 1994). Hg_T concentrations of 4.4 ng l⁻¹ in the Truckee River, downstream of Steamboat Creek, were observed (Wayne and others 1996). There is no doubt that the Steamboat Springs waters are highly elevated in their Hg concentration relative to more pristine runoff waters, with a mean concentration of 57 ng l⁻¹. The three Sierra Nevada mountain streams yield a mean value of 1.5 ng l⁻¹, and even the agricultural ditch waters have concentrations equal or very close to 2.4 ng l⁻¹, the worldwide average riverine concentration, as already mentioned (Table 1). The Creek value is ~38 times greater than the pristine mountain first- and second-order streams flowing into it. The agricultural waters are about 60% enriched in Hg relative to the pristine streams.

The Hg_T concentration at Pleasant Valley was 51 ± 8 ng l⁻¹. This sample is upstream from the major geothermal area of the Steamboat Springs, although warm water at depth exists in this region (Garside and Schilling 1979). This sample represents the closest to the abandoned ore processing facilities north of Washoe Lake. By the Rhodes Road location (Fig. 2), the Hg_T has decreased to 25 ± 2 ng l⁻¹. The sample collected just north of Steamboat Springs (sample 7) has a similar value of 24 ± 1 ng l⁻¹. As one moves further downstream the concentra-

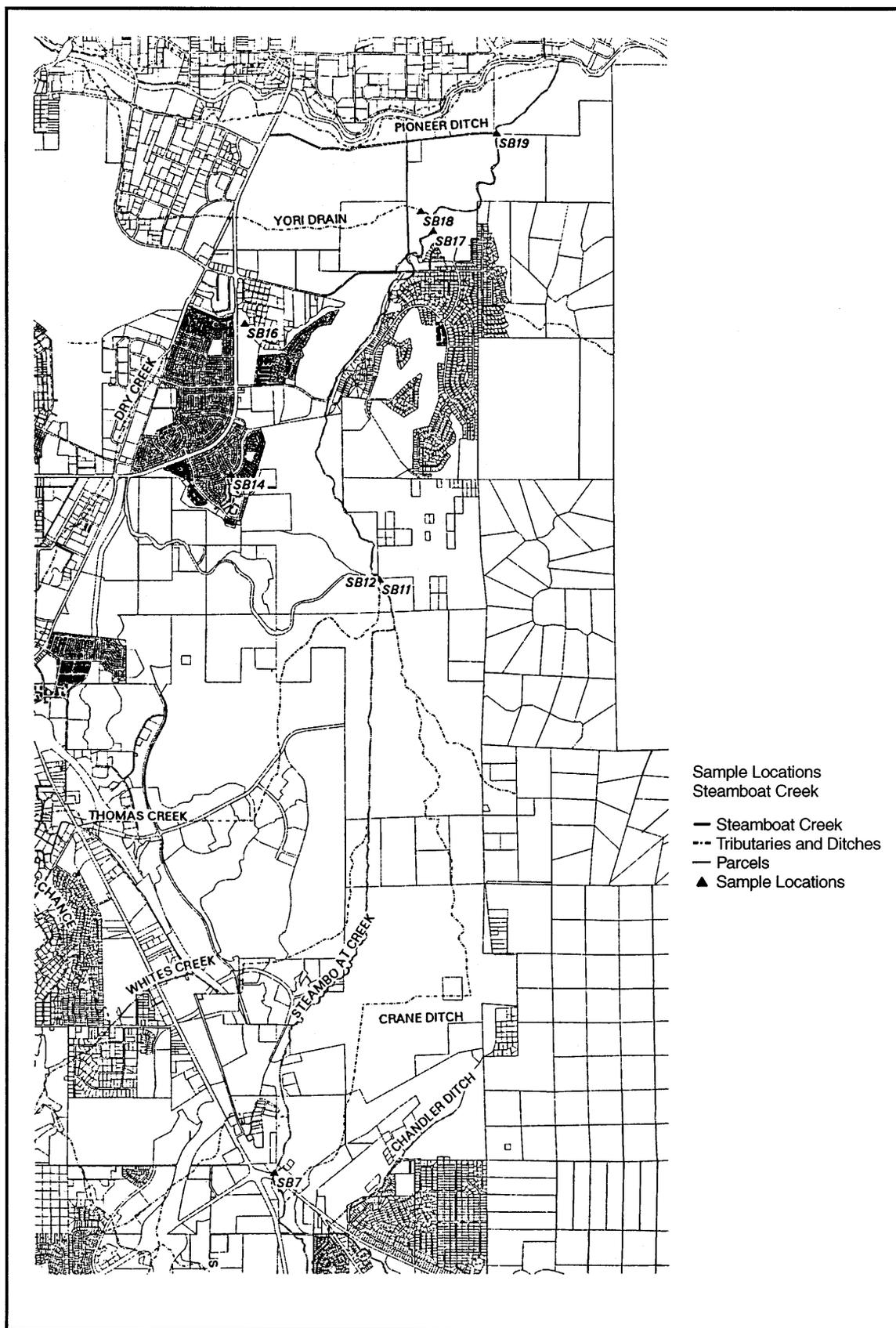


Fig. 3
Northern portion of Steamboat Creek, Nev., with sampling sites SB-7-SB19

tions increase to $74 \pm 2 \text{ ng l}^{-1}$ (sample 11), and the highest values are observed in the farthest downstream (Fig. 3) samples, 82 and 84 ± 2 , respectively. The Cl^- and As data show no systematic trend, although the two lowest Cl^- values are associated with the pristine mountain streams. The higher Cl^- value from Galena Creek may have some geothermal input into it as it follows close to the Steamboat Springs area. The extremely high Cl^- and As concentrations in Steamboat Creek, just north of Steamboat Springs, definitely demonstrate the influence of the geothermal input as the thermal waters are high in Cl^- and As (Garside and Schilling 1979). The agricultural waters can also be enriched in Cl^- and As due both to evapoconcentration and shallow groundwater input (Welch and others 1988).

Discussion

Previous work has shown that gold-silver ore refining/processing activities have caused elevated Hg concentrations downstream from these activities in both waters and sediments of rivers. This work included analysis of both past (Gill and Bruland 1990; Nriagu 1993; Leigh 1994; Callahan and others 1994; Mastrine 1996) and present (Lacerda and others 1991; Nriagu and others 1992) mining activities. The recent work on the Carson River system to the SE of the Steamboat Creek area shows this very dramatically (Warwick and others 1994; Wayne and others 1996; Bonzongo and others 1996a; Miller and others 1995), with Hg_T concentrations as high as $\sim 2100 \text{ ng l}^{-1}$. On the other hand, as already pointed out, the Steamboat Creek watershed lies within a mercuriferous belt characterized by Hg mineralization, thermal spring activity, and slightly elevated atmospheric background levels (Gustin and others 1994). Yet the Pleasant Valley (Fig. 2) sampling site does occur below the extensive geothermal input, and its very high Hg_T concentrations are undoubtedly due to previous Comstock milling operations in the 1860s. So, like the CRLRS, this high value implies that Hg introduced into the environment ~ 130 years ago is still having an overriding affect on the creek today. Unlike the CRLRS, however, the duration of Hg introduction was much less than 30 years ago (Ansari 1989).

The decrease in Hg_T by Rhodes Road (sample 5) is concurrent with an increase in Cl^- , indicating the Hg_T decrease is probably not due to dilution from Galena Creek water (sample 4) but rather to loss of particulate Hg via deposition (Fig. 2). Previous work in the CRLRS (Bonzongo and others 1996a) as well as that of other field locations (Gill and Bruland 1990; Bonzongo and others 1996b; Mastrine 1996) and in the field experiments (Schindler and others 1980; Santschi and others 1986) have shown Hg to be a highly particle reactive element, especially at neutral to alkaline pHs. For example, Bonzongo and others (1996a) found as much as 98% of Hg_T in the CRLRS was associated with the particulate fraction.

The lack of increase in Hg_T as the creek passes through the geothermal waters is a significant observation, especially with the large increases in the more soluble species, Cl^- and As. These data suggest that little Hg_T is actually input into the creek from the springs, or the majority that is, is rapidly removed from the water column onto sediment particles. At Short Lane (sample 11), the concentrations of Hg_T , Cl^- , and As increase again (Fig. 3), even after dilution with more pristine Sierra Nevada stream water (Table 1). All these constituents increased by roughly the amount ($\text{Hg}_T \times 3$, $\text{Cl} \times 2$, and $\text{As } 1.4 \times$), which may suggest simple evapoconcentration to be an important mechanism in this portion of the creek. The last two sampling locations on the creek prior to intersection of the Truckee River (Fig. 3) have higher Hg_T concentrations (82 and 84 ng l^{-1} , respectively), but much lower Cl^- and As values. The Cl^- decrease was ~ 3.4 times, and the As decrease was very similar (~ 3.7 times). A similar Hg_T reduction would have led to values at these locations of $\sim 22\text{--}20 \text{ ng l}^{-1}$. Since Boynton Slough and York Ditch have much lower Hg_T concentrations than the Steamboat Creek water, the increase in Hg_T cannot be due to these agricultural waters. Rather, increased sediment suspension in this portion of the creek may be the only logical source of the increase in Hg_T . If true, this implies that the entire creek bed is contaminated with Hg-enriched sediments.

What the data do indicate is the following:

1. There has been Hg input into Steamboat Creek from previous Ag-Au ore processing.
2. There appears to be little measurable Hg_T input from the geothermal area at Steamboat Springs. The caveat is, however, that Steamboat Springs was not directly sampled, so that this observation is based on creek samples made between the geothermal input.
3. There is little apparent Hg_T input from agricultural runoff as the ditch waters have concentrations very similar to the pristine mountain streams (i.e., 2.3 ng l^{-1} vs. 1.5 ng l^{-1}).
4. There is no way, from the data presently available, to evaluate whether there has been any impact on the creek from the highly Hg-enriched region to the east of the watershed (i.e., Castle Rock mining area).

The Hg_T concentrations in the Truckee River downstream of the Steamboat Creek input is 4.4 ng l^{-1} (Wayne and others 1996). There are no data from the Truckee above Reno. However, assuming that the Truckee River above Reno has similar Hg_T as the three pristine streams draining the Sierra Nevada reported here and in Wayne and others (1996), an average Hg_T of 1.2 ng l^{-1} is obtained [pristine lake waters in the Sierra Nevada have even lower Hg_T concentrations as Gill and Bruland (1990) have reported a value of 0.6 ng l^{-1} for Silver Lake]. Using this value of 1.2 ng l^{-1} as the Truckee River value and 83 ng l^{-1} as the input value from Steamboat Creek into the lower Truckee and the flow rates from the USGS gaging stations in 1993 water year, a yearly flux of Hg_T into the lower Truckee can be computed. This yields an input of Hg_T from the Truckee River upstream of Reno to be

Table 2

Steamboat Springs water quality data from the Nevada Department of Environmental Protection (NDEP), 13 April 1993. Sample numbers same as Table 1 (as in $\mu\text{g l}^{-1}$, Cl^{-} on $\mu\text{Mol l}^{-1}$) [* Steamboat Creek proper, ND=no data, ° previously reported in Wayne and others (1996); all other – triplicate analysis, + these sample sites are numbered according to the ongoing sampling program of the NDEP; sampling locations 2, 6, 9, 13 and 15 were not samples]

sample no. +	As	Cl^{-}
1*	ND	0.53
3*	ND	0.22
4°	ND	0.39
5*	5	0.68
7*	204	2.93
8°	ND	< 0.03
10°	ND	< 0.03
11*	295	6.00
12	134	2.56
14	ND	0.14
16	14	0.45
17*	76	1.75
18	8	0.38
19*	84	ND

~ 1.25 kg year⁻¹ and that from Steamboat Creek to be ~ 1.45 kg year⁻¹. These calculations demonstrate that the over 50% of the Hg_T entering the lower Truckee could be from Steamboat Creek and is undoubtedly due to previous Hg contamination from Comstock mining days over 130 years ago. What percentage of this Hg actually escaped the river system and is either diverted via the Derby Dam into the Carson River drainage or reaches the terminus of the Truckee River system, Pyramid Lake, is unknown. Hg_T concentrations of 1.9 ng l⁻¹ have been reported for Pyramid Lake by Gill and Bruland (1990), indicating that the lake has probably been little impacted by the Steamboat Creek outflow. It should be emphasized, however, that 1993 was a drought year in the Truckee River basin, and therefore the percentage Hg flux calculated here probably represents an extreme case. Higher flows in the Truckee would “dilute out” this Steamboat Creek input.

Conclusions

The waters from Steamboat Creek and its tributaries have been analyzed using ultraclean laboratory techniques for Hg_T . The waters of the creek itself have much higher concentrations than those of pristine runoff waters. Concentrations are, in fact, higher than those from runoff waters that had known Hg contamination (e.g., Gill and Bruland 1990; Nriagu and others 1992; Wayne and others 1996; Bonzongo and others 1996a). The data indicate that only former Au/Ag processing is a definite source of Hg to the creek. The legacy of Hg contamination from the

Comstock mining appears also to have affected areas to the west of Virginia City where some of the initial ore milling took place.

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