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Trace-Element Enrichment in Streambed Sediment and Crayfish, Carson and Truckee Rivers, Nevada and California, September 1992

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ABSTRACT

The Carson and Truckee River Basins in Nevada and California are part of the U.S. Geological Survey National Water-Quality Assessment Program. This program is designed to determine the status and trends of water quality in the United States. Concentrations of aluminum, arsenic, chromium, copper, lead, mercury, nickel, selenium, silver, vanadium, and zinc in streambed sediments and in samples of the western crayfish (*Pacifastacus leniusculus*) are summarized and compared. The samples were collected in September 1992 from 11 sites on the Carson and Truckee Rivers.

Past mining and ore-milling practices have enriched the Carson River bed sediments and crayfish with several trace elements. Enriched concentrations of aluminum, arsenic, chromium, copper, lead, mercury, nickel, and selenium were measured in streambed sediment collected at the East Fork Carson River near Gardnerville, Nev. Possible sources of these trace elements include natural mineral deposits and areas affected by human activity. Mercury and silver were enriched in streambed sediment downstream from Carson City, Nev., as a result of historical ore milling during the Comstock era. Crayfish downstream from the East Fork Carson River near Gardnerville were moderately to highly enriched with aluminum, arsenic, mercury, and nickel. Arsenic concentrations were significantly higher in the Carson River bed-sediment samples than in the Truckee River bed-sediment samples.

Urban activity may be the primary source of trace-element enrichment in Truckee River bed-sediment and crayfish samples. However, agricultural activity, historical ore milling, and geothermal discharge also may contribute trace elements to the river. Bed sediment and crayfish from the Truckee River at Reno and downstream were enriched with arsenic, lead, mercury, and silver.

Statistically significant relations were measured between arsenic, mercury, and silver concentrations in bed-sediment and crayfish samples from the Carson and Truckee Rivers. These relations indicate that arsenic, mercury, and silver were bioavailable and were bioaccumulated in crayfish, especially in the Carson River.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) began intensive water-quality investigations in 20 river basins across the United States. These 20 study areas are part of the National Water-Quality Assessment (NAWQA) Program designed to assess water-quality conditions, determine trends, and identify the major factors that affect surface- and ground-water quality in the United States. The study basins drain some of the most densely populated watersheds in the United States (Hirsch and others, 1988; Leahy and others, 1990). NAWQA is unique among the national programs implemented by USGS because it integrates physical, chemical, and biologic (ecological and tissue) data to meet its goals. Crawford and Luoma (1993) summarize the objectives of tissue sampling for the NAWQA programs.

Kick sampling for crayfish in the Truckee River at Lockwood, Nev., September 1992. Photograph by Ronald P. Collins, U.S. Geological Survey.

NAWQA's multidimensional approach to surface-water-quality sampling attempts to overcome the limitations of methods commonly used to assess river quality. Normally, water-column samples are collected over space and time in a random, systematic, or stratified manner (Ellis and others, 1980; Gilbert, 1987). Unfortunately, these sampling designs provide only "snapshots" of water quality in a river or stream. These snapshots usually miss contaminants entering a river during episodic events, such as storm runoff, and can miss those trace elements and organic compounds associated with streambed particulate matter. Water-column sampling can provide useful data for elements or chemicals that are primarily in the water column such as major cations and anions or sewage effluent that enters a river in a continuous, nonepisodic manner. Contaminants that might be missed during routine water sampling can be detected by analyzing either bed sediment (Horowitz, 1991) or biological tissue (Luoma and Carter, 1991).

Researchers indicate that analyzing trace elements in bed sediments is valuable for tracking anthropogenic contamination. Bed sediment in streams that receive urban runoff commonly is enriched with cadmium, chromium, copper, lead, mercury, and zinc (Driver and others, 1985; Ellis and Mustard, 1985; Porter and others, 1995). Trace-element enrichment in bed sediments by acid mine drainage was seen many miles along the Blackfoot (Moore and others, 1991) and Clark Fork (Axtmann and Luoma, 1991) Rivers in Montana. Also, silver and lead concentrations in bed sediments were used to track the nearshore movement of sewage effluent along the southern California coast (Sanudo-Wilhelmy and Flegal, 1992).

Bed sediments provide a better measure of trace-element contamination than aquatic biota, but aquatic biota are best used to measure the bioavailability of that contamination and, therefore, the potential effects on ecological integrity (Clements, 1991). Tissue analysis provides a measure of bioaccumulation (ingestion minus excretion) and is the least ambiguous measure of trace-element bioavailability (Luoma and Carter, 1991). Much information exists that documents bioavailability and bioaccumulation of trace elements in aquatic biota. Luoma and Carter (1991) discuss some of the research on bioavailability, dose response, effects of environmental conditions on uptake and elimination of trace elements from aquatic biota, and the difficulties in relating not only environmental concentrations to bioaccumulation but also to individual and community effects.

Many different organisms have been used in trace-element bioaccumulation studies, including several crayfish species. Stinson and Eaton (1983) call the crayfish *Pacifastacus leniusculus* a "useful biological indicator of trace-metal contamination," whereas Alikhan and others (1990) suggest that the crayfish *Cambarus bartoni* is generally a reliable indicator of trace metals except copper and nickel. Rada and others (1986) also conclude that crayfish may be better than fish for describing localized metal contamination because crayfish have limited mobility.

Purpose and Scope

This report describes the distribution of trace elements in bed sediments and crayfish (*Pacifastacus leniusculus*) at 11 sites in the Carson and Truckee Rivers, west-central Nevada and east-central California. The report (1) identifies areas where streambed sediments were enriched with aluminum, arsenic, chromium, copper, lead, mercury, nickel, selenium, silver, vanadium, and zinc; (2) identifies relations among trace elements in streambed sediment that may suggest a source of enrichment; (3) describes trace-element concentrations in crayfish (*Pacifastacus leniusculus*) at 11 sites in the Carson and Truckee Rivers; and (4) compares trace-element concentrations in streambed sediment to concentrations in crayfish. The results may have wide utility, particularly in areas where crayfish of the genus *Pacifastacus* exist. The crayfish genus *Pacifastacus* is found in British Columbia, Canada, and in California, Idaho, Montana, Nevada, Oregon, Washington, Wyoming, and Utah; however, *Pacifastacus leniusculus* is found only in California, Idaho, Nevada, Oregon, and Washington (Pennak, 1989).

Study Area

The Carson and Truckee Rivers flow within two separate, but adjacent, closed basins (fig. 1) in the eastern Sierra Nevada Physiographic Province and the western Basin and Range Physiographic Province. The basins drain a combined area of about 7,200 square miles (mi^2; Covay and others, 1996). The Carson River flows 133 miles (mi) from an altitude of 9,760 feet (ft) above sea level in the eastern Sierra Nevada to 4,160 ft at Lahontan Reservoir (Brown and others, 1986). Lahontan Reservoir currently traps most of the sediment and water that previously would have reached the hydrologically closed basin known as Carson Sink, east of the reservoir. The Truckee River flows 120 mi from the outlet at Lake Tahoe, Calif. (altitude about 6,218 ft), to Pyramid Lake, Nev. (a terminal lake, altitude about 3,790 ft; Brown and others, 1986). The average annual precipitation in the upper parts of both basins is nearly 30 inches (in.), while annual precipitation in the lower parts averages about 5 in. (Covay and others, 1996).

Consolidated rocks form the mountain blocks in the study area and also underlie partly consolidated and unconsolidated sediments that fill the valleys. Hydrogeologic units that form the consolidated rocks are collectively referred to as bedrock, and sedimentary units are referred to as basin-fill sediments. The Carson River Basin is within one of three global mercuriferous belts and is exemplified by the Castle Peak District that produced nearly 84 tons of mercury in the early 1900's (Gustin and others, 1994). Cinnabar, the natural form of mercury, is deposited by geothermal activity at Steamboat Springs (Bailey, 1964), 11 mi south of Reno, Nev., in the Truckee River Basin.

A complex mixture of mining, urban, and agriculture land uses is found in both basins. Information about the 11 sites sampled in both basins—5 in the Carson River Basin and 6 in the Truckee River Basin—including potential anthropogenic sources of trace elements in each river basin is given in table 1. The two major mining activities in the Carson River Basin (Leviathan Mine and Comstock Area) were closely related for a time. The Leviathan Mine, near Markleeville, Calif., began producing chalcanthite, a copper sulfate mineral (California Department of Water Resources, 1991), in the early 1860's and was active intermittently (1860-72, 1935-41, 1951-62) until it closed permanently in 1962. During this time, about 22 million tons of overburden that contained large amounts of sulfide minerals were discarded in the area surrounding the mine (Hammermeister and Walmsley, 1985, p. 1). Chalcanthite was used to refine silver from ore originating in the Comstock mines (Hammermeister and Walmsley, 1985, p. 1; California Department of Water Resources, 1991).

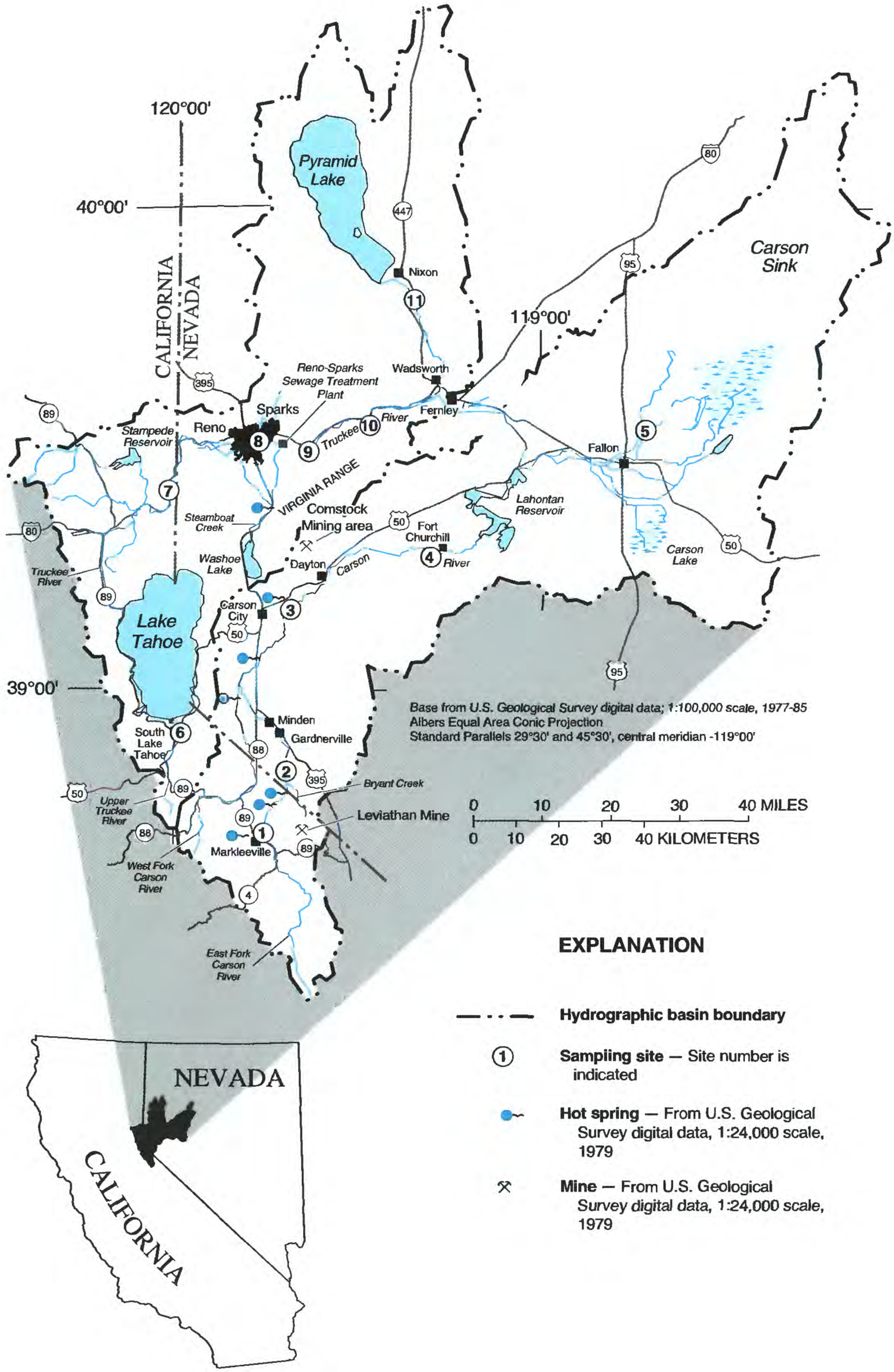

Figure 1. Carson and Truckee River Basins in Nevada and California, with sampling sites identified.

Table 1. Stream sites in Carson and Truckee River Basins where bed-sediment and crayfish (*Pacifastacus leniusculus*) samples were collected, September 1992

[Abbreviation: e, estimated]

Site no. (fig. 1)	Site name	Distance from origin[1] (river miles)	Principal anthropogenic sources of trace elements
1	East Fork Carson River near Markleeville, Calif.	37.1	Markleeville, Calif.; State Highway, mine tailings.
2	East Fork Carson River near Gardnerville, Nev.	52.0	Acid mine drainage to an upstream tributary (Bryant Creek); mine tailings.
3	Carson River near Carson City, Nev.	88.5	Carson City, Nev.; light agriculture (alfalfa and dairy); mine tailings from Comstock era.
4	Carson River near Fort Churchill, Nev.	121.0	Carson City, Nev.; light agriculture; mine tailings from Comstock era.
5	Carson River at Tarzyn Road near Fallon, Nev.	184e	Fallon, Nev.; agriculture; mine tailings from Comstock era.
6	Upper Truckee River at South Lake Tahoe, Calif.	[2]1.0	South Lake Tahoe, Calif.; State and Federal highways.
7	Truckee River at Farad, Calif.	33.9	Federal highway; Tahoe City and Truckee, Calif.
8	Truckee River at Reno, Nev.	57.2	Reno, Nev., urban area.
9	Truckee River at Lockwood, Nev.	66.3	Reno-Sparks, Nev., urban area; tertiary treated sewage effluent; mine tailings.
10	Truckee River at Clark, Nev.	77.7	Reno-Sparks, Nev., urban area; tertiary treated sewage effluent; mine tailings.
11	Truckee River at Nixon, Nev.	113.1	Light agriculture (alfalfa); Reno-Sparks, Nev., urban area; Wadsworth, Nev.; tertiary treated sewage effluent; mine tailings.

[1] Origin of Truckee River is Lake Tahoe at Tahoe City, Calif.; origin of Carson River is headwaters of East Fork Carson River at altitude of 9,670 feet above sea level.

[2] Distance upstream from Lake Tahoe at South Lake Tahoe, Calif., in river miles.

In 1859, a gold- and silver-rich ore body (the Comstock Lode) was discovered in the Virginia Range bordering the Carson River Basin. This discovery began a 60-year period of ore processing in the middle part of the Carson River Basin. During the period of peak production (1859-80), about 7,500 tons of elemental mercury were lost in the middle to lower Carson River Basin when mercury amalgamation was used to recover silver and gold from bulk ore (Smith, 1943, p. 257). Several papers have reported the extent of mercury contamination in streambed sediments and aquatic biota from the lower Carson River (Van Denburgh, 1973; Richins and Risser, 1975; Cooper and others, 1985; Gustin and others, 1994; Lawrence and Bevans, 1994). Mercury concentrations as high as 20 micrograms per gram ($\mu g/g$, dry weight) in bed sediment from Lahontan Reservoir (Van Denburgh, 1973) and as high as 48 $\mu g/g$ (dry weight) in crayfish from the Carson River near Fort Churchill (Lawrence and Bevans, 1994) were measured.

Historically, the major mining activity in the Truckee River Basin was Comstock ore processing in the upper part of the Steamboat Creek drainage basin. This tributary enters the Truckee River at river mile 62.7 (Brown and others, 1986, p. 107). In the Truckee River Basin, maximum mercury concentrations of 1.2 and 0.58 $\mu g/g$ (dry weight) were measured in bed sediment in 1971-72 (Van Denburgh, 1973) and 1992 (Lawrence and Bevans, 1994), respectively. In comparison, crayfish collected from the Truckee River in 1992 had a maximum mercury concentration of 0.49 $\mu g/g$ (dry weight).

Runoff from urban and agricultural activities is a potential source of trace elements to both rivers. Both the Carson and Truckee River Basins contain major highways that either intersect or parallel the rivers. The Carson River Basin, which contains several small towns, is not as extensively urbanized as the Truckee River Basin, which contains the Reno-Sparks urban area and several small towns. Many urban areas produce runoff containing high concentrations of trace elements, especially lead, zinc, copper, chromium, and mercury (Driver and others, 1985; Ellis and Mustard, 1985; Licsko and Struger, 1995). Until recently, urban runoff in the Carson and Truckee River Basins flowed unimpeded into the river. However, runoff detention ponds are now required in areas with new construction. Since 1987, sewage effluent has not been discharged to the Carson River (Gary Hoffman, Carson City Utility Department, oral commun., 1994). Tertiary-treated sewage effluent (nitrogen and phosphorus removal) is discharged to the Truckee River, by way of Steamboat Creek, downstream from the cities of Reno and Sparks. During drought, streamflow in the river below Reno and Sparks may consist almost entirely of tertiary-treated sewage effluent. Irrigation drainage from agricultural activity in the lower parts of the Carson River Basin (primarily alfalfa, small grains, melons, and dairy) has been shown to adversely affect water quality (Hoffman and others, 1990; Rowe and others, 1991).

INVESTIGATION METHODS

Sample collection and processing methods were designed to minimize sample contact with all metal surfaces. Field personnel wore latex gloves at all times and sampling equipment and containers were either Teflon[1], polyethylene, polypropylene, or epoxy-coated metal. All equipment and containers were washed with laboratory-grade detergent, rinsed with trace-element-free, de-ionized water, rinsed with 5-percent nitric acid, rinsed again with de-ionized water, and then rinsed with native stream water prior to sampling at each site.

Bed Sediment

Bed-sediment samples were collected and processed according to USGS NAWQA protocols (Shelton and Capel, 1994). One composite sample was collected from each site in the study area. A composite sample consisted of five subsamples collected from the top 1 in. of sediment in depositional areas such as pools, in the lee of boulders and trees, or along stream-channel margins. A Teflon spatula was used to scoop sediment from the stream bottom into a Pyrex glass bowl. The sediment was mixed and wet-sieved through 63-micrometer (μm) nylon cloth using native water. A 500-milliliter (mL) polyethylene jar was used to ship approximately 10 grams of sediment (dry weight) for analysis at a U.S. Geological Survey laboratory.

[1]Use of trade names in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Government.

Bed sediment collection in a small depositional area along the Truckee River at Clark, Nev., September 1992. Photograph by Ronald P. Collins, U.S. Geological Survay.

Bed-sediment samples were prepared for trace-element analysis using total acid digestion. In the laboratory, the composited samples from each site were air dried, pulverized, and mixed to ensure a homogenous sample. Two subsamples were digested with different acids depending upon the trace elements to be analyzed. One subsample was prepared for an analysis of all trace elements except mercury by digestion with a mixture of nitric, hydrochloric, and hydrofluoric acids. The other subsample was prepared for mercury analysis by digestion with nitric acid and sodium dichromate. Arsenic and selenium concentrations were determined using hydride generation atomic-absorption spectrophotometry (Welsch and others, 1990). Mercury concentrations were determined using continuous-flow, cold-vapor atomic-absorption spectrophotometry (O'Leary and others, 1990). All other trace-element concentrations were determined using inductively coupled plasma-atomic emission spectrometry (Briggs, 1990).

Crayfish

The handling, processing, and quality control of crayfish samples for trace-element analysis followed protocols developed by the U.S. Geological Survey NAWQA program (Crawford and Luoma, 1993). One composite sample was collected at each site. Each composite consisted of 10 crayfish (5 males and 5 females) that were collected at each site by hand, traps, or electroshocking. Crayfish were depurated for 48 hours in polyethylene tubs containing native stream water at 20°C. After depuration, whole crayfish with chelapeds removed were sealed in plastic bags, frozen with dry ice, and shipped to the USGS National Water Quality Laboratory, in Arvada, Colo., for analysis.

At the laboratory, the composite sample of 10 crayfish collected at each site was ground up and homogenized. A subsample from each composite was digested, using nitric acid in a method similar to the U.S. Environmental Protection Agency method 200.3 (U.S. Environmental Protection Agency, 1991). Wet weight, dry weight, percent water, percent lipid, and 21 trace-element concentrations were determined for each subsample. Trace elements in tissue extracts were analyzed using inductively coupled plasma mass spectrometry (aluminum, iron, arsenic, cobalt, lead, nickel, selenium, silver, and vanadium), inductively coupled atomic-emission spectrometry (chromium, copper, and zinc), and cold-vapor atomic-absorption spectrometry (mercury; K.D. Pirkey and B.F. Connor, U.S. Geological Survey, written commun., 1993).

The trace elements discussed in this paper were those that represented a trace-element component from factor analysis and those such as arsenic, silver, and mercury that previous studies had identified as bed-sediment contaminants (Van Denburgh, 1973; Cooper and others, 1985). Thus, included in this report are bed-sediment concentrations of aluminum, arsenic, chromium, cobalt, copper, iron, lead, mercury, nickel, selenium, silver, vanadium, and zinc; and crayfish concentrations of aluminum, arsenic, cobalt, copper, iron, lead, mercury, nickel, silver, vanadium, and zinc. Few crayfish contained chromium or selenium in concentrations above laboratory reporting levels. Cobalt and iron are discussed only in relation to the results of factor analysis.

Crayfish trap in place in the East Fork Carson River below Markleeville, Calif., September 1992. Photograph by Stephen J. Lawrence, U.S. Geological Survey.

Data Analysis

Bed-sediment and crayfish data were transformed to ranks before statistical analyses. Bed-sediment concentrations of aluminum, chromium, iron, silver, and vanadium were adjusted for the influence of total organic carbon (TOC) because of the high positive correlations between those elements and TOC (r greater than 0.80, *p* less than 0.001). The influence of TOC was factored out of aluminum, chromium, iron, silver, and vanadium concentrations by regressing the trace-element concentration with TOC concentration, computing residuals, and adding the element mean to the residuals (Helsel and Hirsch, 1992, p. 329-333).

Two methods were used to explore trace-element relations within bed-sediment and crayfish samples: (1) A comparison of trace-element concentrations at each site to concentrations at a minimally affected background site; and (2) statistical analyses using nonparametric methods (Conover, 1980). Trace-element concentrations in bed-sediment and crayfish samples collected at sites in the Carson River were compared to those for the East Fork Carson River below Markleeville, Calif. (site 1, fig. 1). Trace-element concentrations in bed-sediment and crayfish samples collected at sites in the Truckee River were compared to those for the Truckee River at Farad, Calif. (site 7, fig. 1). The potential for trace-element contamination by the land uses upstream from sites 1 and 7 was minimal (table 1). Statistical methods used in this report, all of which were nonparametric (data transformed to ranks), included: (1) factor analysis using principal components (PCA) with orthogonal and oblique rotations, used to identify multivariate correlations among trace elements in the bed-sediment and crayfish data sets; (2) Spearman's rank correlation method and linear regression, used to identify correlations and regressions, respectively, between bed-sediment samples and crayfish samples; and (3) a Mann-Whitney U-test, used to compare crayfish sizes among sites.

The PCA method is used for examining the interrelations among variables and identifies independent groups of variables that explain or account for a part of the variability in a data set (Rummel, 1970, p. 13-21). In this report, the variables are trace-element concentrations. The groups commonly are called components because they represent components explaining the variability in the data. The components that explain most of the variability in the data are called the principal components. Variability in this context is a two-dimensional entity that refers to the differences in each trace-element concentration among all the bed-sediment or crayfish samples collected from the Carson and Truckee Rivers and the concentration differences among all trace elements at a particular site. Each principal component identifies the common variability in the data, and each component can be interpreted as representing a common source or process affecting the trace elements in that component. A data set with no variability will result in one component. The data used in the PCA are not limited to a particular type—any square matrix can be analyzed.

The initial data matrix for the PCA in this study consisted of nonparametric correlation coefficients. A matrix of correlation coefficients is the most commonly used data matrix in PCA (Rummel, 1970, p. 14). Although trace-element concentrations were transformed to ranks for this report, data do not have to be normally distributed unless tests for statistical significance are applied to the components (Rummel, 1970, p. 14). Orthogonal and oblique rotations are commonly used to optimize the variability explained by a component. Components that are orthogonal are uncorrelated with each other, whereas components that need an oblique rotation to optimize variability are correlated.

In this study, trace-element components from PCA of bed-sediment samples were optimized with the varimax method, a type of orthogonal rotation, whereas trace-element components from the PCA of crayfish samples were optimized with an oblique rotation. Because each component is a group of related trace elements with similar variability in the data set, a component may identify a group of trace elements that has a common source or that is affected by a common process (pie chart, fig. 2). PCA can be used to areally map each component by assigning a score to each sample in the data set (bar chart, fig. 2). The score indicates the strength of the relation between a sample and a principal component. A score greater than 1.0 suggests that the source or process described by a principal component is strongly influencing the variability of the trace element in a sample (bar chart, fig. 2).

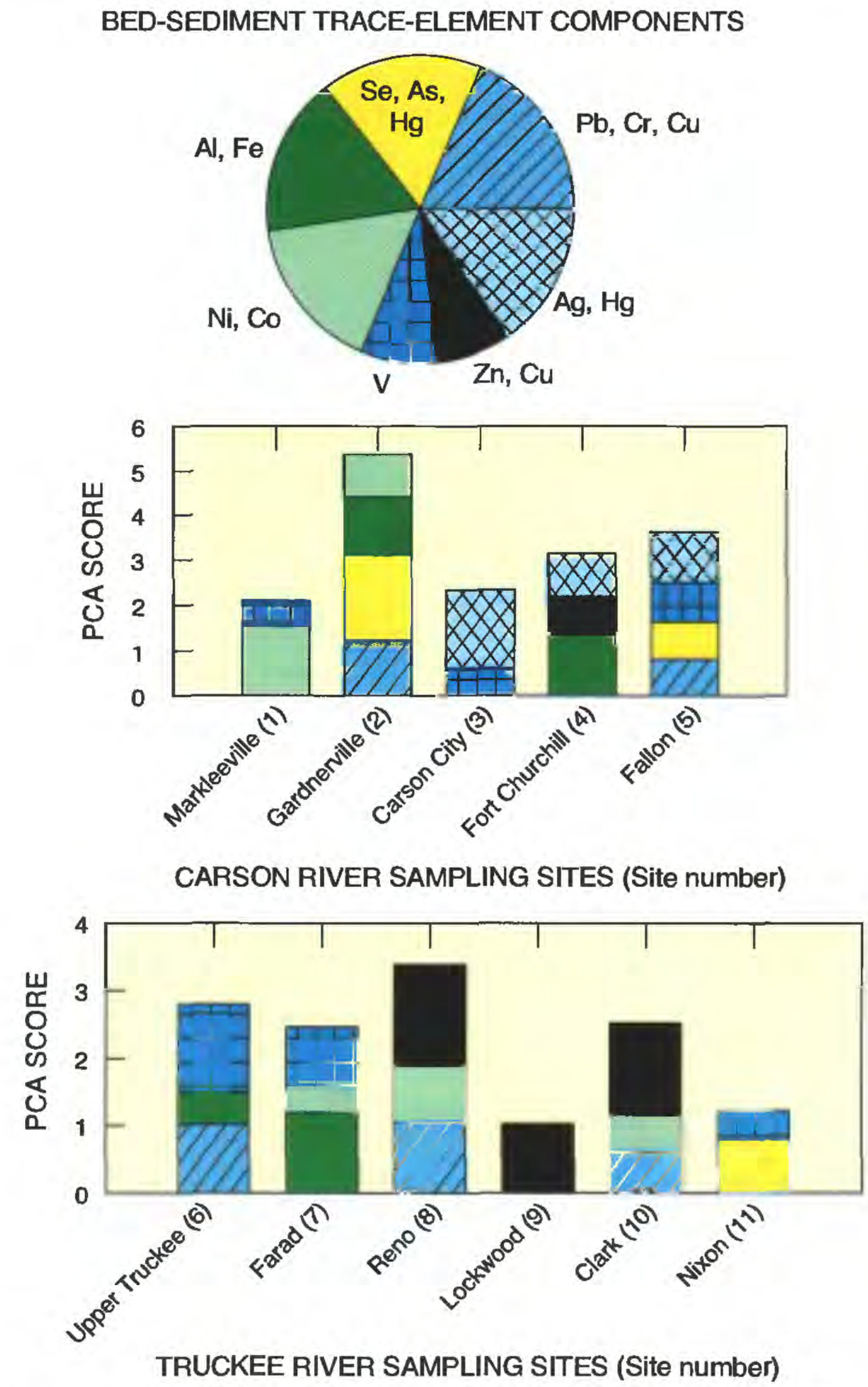

Figure 2. Trace-element components that account for 98 percent of variability in bed-sediment samples from Carson and Truckee River Basins (pie diagram), and trace-element components that account for variability at each sampling site in Carson and Truckee River Basins (bar charts). Scores quantify a component's importance in accounting for total trace-element variability at each site. Abbreviation: PCA, principal components analysis.

TRACE ELEMENTS

Concentrations of 11 trace elements determined from bed-sediment samples in both river basins, including element concentrations adjusted for TOC, are shown in table 2. Median arsenic and mercury concentrations were markedly higher in the Carson River bed-sediment samples than in those of the Truckee River. The PCA showed that seven trace-element components accounted for 98 percent of the variability in the trace-elements measured in the Carson River and Truckee River bed-sediment samples (pie chart, fig. 2). The remaining 2 percent is variability associated with sampling and analytical error.

The PCA results show that the nickel and cobalt component, and the vanadium component scored high in bed sediments at the two background sites: Carson River near Markleeville, Calif. (site 1), and Truckee River at Farad, Calif. (site 7). The aluminum and iron component also scored high at the Farad site (fig. 6). These trace elements probably were geologically controlled because both background sites are minimally affected by human activities. The decrease in vanadium and cobalt downstream suggests dilution of bed sediments as anthropogenically derived and geologically different sediments are transported to both rivers.

Concentrations of aluminum, arsenic, chromium, copper, lead, mercury, nickel, selenium, silver, vanadium, and zinc in crayfish samples from 10 sites on the Carson and Truckee Rivers are shown in table 3. Crayfish were not found at the Fallon site (site 5). Chromium and selenium concentrations were generally less than laboratory reporting limits (table 3). Mean concentrations of aluminum, arsenic, cobalt, copper, iron, lead, mercury, silver, and vanadium in Carson River crayfish were greater than those concentrations in Truckee River crayfish (table 3). Mean nickel and zinc concentrations in Carson River crayfish were similar to those in Truckee River crayfish.

Nonparametric analysis of variance showed that median crayfish length was significantly different among sites (p equals 0.004) and generally increased downstream (fig. 3). The increase in crayfish length paralleled the downstream increase in water temperature (fig. 3). Thus, crayfish were probably larger in the lower reaches of both rivers because of faster growth rather than older ages. This is an important distinction because older individuals tend to have greater trace-element concentrations than younger individuals due to longer accumulation times (Newman and Heagler, 1991). Although nonparametric correlation showed that arsenic, mercury, and silver concentrations increased as the median crayfish length increased (r equals 0.81, p less than 0.005; r equals 0.77, p less than 0.01; and r equals 0.88, p less than 0.0001, respectively), these may be spurious correlations because arsenic, mercury, and silver concentrations in bed sediment also were higher in the lower reaches of both rivers (table 2).

Table 2. Trace-element concentrations in bed-sediment samples for 11 sites in Carson and Truckee River Basins, Nevada and California, September 1992

[Abbreviation: TOC, total organic carbon. Except where indicated, all units are micrograms per gram, dry weight]

Trace constituents	Sampling sites (figure 1 and table 1)												
	Carson River						Truckee River						
	1	2	3	4	5	Median	6	7	8	9	10	11	Median
TOC, in percent, dry weight	2.0	1.4	3.1	1.5	5.7	2.0	3.1	0.8	3.7	3.3	3.3	4.9	3.3
Aluminum, in percent (Al), dry weight	9.2	8.9	7.5	8.7	6.3	8.7	8.6	9.7	8.2	7.4	7.9	3.9	8.1
Aluminum, TOC-adjusted, in percent, dry weight	4.6	6.3	2.1	6.0	1.1	4.6	2.7	12.6	2.2	2.2	2.4	.8	2.3
Arsenic (As)	20	80	40	30	90	40	10	6	10	20	20	10	10
Chromium (Cr)	50	90	50	40	35	50	55	60	40	45	40	20	40
Chromium, TOC-adjusted	40	75	50	25	55	50	60	50	50	50	40	40	50
Cobalt (CO)	20	30	20	20	20	20	20	20	20	15	20	10	20
Copper (Cu)	40	70	40	40	40	40	30	40	60	50	55	25	45
Iron, in percent (Fe), dry weight	5.0	5.0	4.0	4.5	4.0	4.5	5.0	5.0	4.0	4.0	4.5	2.0	4.2
Lead (Pb)	20	30	20	10	30	20	20	10	70	20	20	8	20
Mercury (Hg)	.2	2.2	4.7	.26	5.9	2.2	.02	.02	.17	.6	.45	.05	.11
Nickel (Ni)	30	40	20	20	20	20	20	20	25	20	20	10	20
Selenium (Se)	.6	9.0	.5	.6	1.3	.6	.3	.1	.3	.8	.6	1.5	.45
Silver (Ag)	.2	.1	1.0	.4	1.4	.4	.1	.1	.3	.6	.5	.1	.2
Silver, TOC-adjusted	.1	.1	.3	.3	.2	.2	<.1	.1	.1	.2	.2	<.1	.1
Vanadium (V)	150	150	130	140	110	140	160	170	120	120	120	110	120
Vanadium, TOC-adjusted	140	130	140	120	140	140	160	140	130	120	120	130	130
Zinc (Zn)	110	90	130	130	110	110	90	100	210	140	150	50	120

Carson River

Bed Sediment

Trace-element concentrations in Carson River bed sediments are given in table 2. Although natural mineral deposits might contribute trace elements, several trace elements from past mining practices have clearly enriched the streambed sediments. Silver and mercury were enriched in Carson River bed sediments because of historical mining and milling of gold and silver ore. Mill tailings still exist along the Carson River and probably continue to erode into the river channel.

A Carson River bed-sediment sample was considered enriched when the trace-element concentration was at least 10 percent greater than the concentration in the Markleeville sample (site 1). The Gardnerville and Fallon samples (sites 2 and 5) were enriched in eight trace elements (fig. 4). The Carson City sample (site 3) was enriched in six trace elements. The sample at the Fort Churchill State Park (site 4) was enriched in four trace elements.

The Gardnerville sample was slightly enriched (1.1 to 1.5 times higher than Markleeville) in aluminum and nickel; moderately enriched (1.6 to 2.0 times higher) in chromium, copper, and lead; and greatly enriched (more than 2.0 times higher) in arsenic, mercury, and selenium (fig. 4). The PCA results show that four components scored high in the bed-sediment sample from the Gardnerville site: Pb-Cr-Cu; Se-As-Hg; Al-Fe; and Ni-Co (fig. 2). These results suggest that trace elements at this site probably came from several different sources or were affected by different processes. Three possibilities are (1) erosion and transport of natural mineral deposits, (2) soil erosion and acid mine drainage from Leviathan Mine, or (3) soil erosion and mine drainage from other small, abandoned mines in the Carson River Basin upstream from the Gardnerville site. Bryant Creek might be a conduit for trace element transport from the Leviathan Mine area to the East Fork Carson River (Hammermeister and Walmsley, 1985). Bryant Creek drains a large part of the Leviathan Mine area and enters the East Fork Carson River about 4.6 mi above the Gardnerville sampling site (Brown and others, 1986). The Leviathan Mine was an open-pit sulfur mine before it was abandoned in 1962 (Hammermeister and Walmsley, 1985).

The correlated concentrations of arsenic, selenium, and mercury in the Gardnerville sample may result from several possible sources. Research has shown that arsenic and selenium contamination can result from irrigation drainage (Hoffman and others, 1990; Seiler, 1996). An area adjacent to the East Fork Carson River, about 5 mi upstream from the Gardnerville site, is irrigated for hay and pasture production on soils classified as saline and alkaline (Glenn W. Hess, U.S. Geological Survey, oral commun., 1997; Candland, 1984). Other potential sources of the high arsenic and mercury in the Gardnerville sample include abandoned mines in the basin, and the discharge of several geothermal springs to the East Fork Carson River upstream from the Gardnerville site (U.S. Geological Survey topographic map, 7.5-minute series, Carters Station, Nev.-Calif., quadrangle). Water from geothermal springs can contain high amounts of arsenic, zinc, and small amounts of mercury and silver (Garside and Schilling, 1979).

The Carson City (site 3) bed-sediment sample was slightly enriched in chromium, lead, and zinc; moderately enriched in arsenic; and greatly enriched in mercury and silver (fig. 4). The PCA results show that two components scored high in the bed-sediment sample at Carson City: V; and Ag-Hg (fig. 2). During the Comstock era, high-grade silver ore was processed in stamp mills

Table 3. Trace-element concentrations and characteristics of composited samples of crayfish (*Pacifastacus leniusculus*) for 10 sites in Carson and Truckee River Basins, Nevada and California, September 1992

[Abbreviation: SD, standard deviation in inches; NA, not applicable. Symbol: --, not determined. Except where indicated, all values are in micrograms per gram, dry weight, based on a composite sample of 6-11 individuals]

Characteristic or trace element	Sampling sites[1] (figure 1 and table 1)											
	Carson River					Truckee River						
	1	2	3	4	Median	6	7	8	9	10	11	Median
Mean length[2]	3.4	3.7	3.9	4.0	NA	3.4	3.6	3.4	3.7	3.9	3.5	NA
(SD)	(.3)	(.2)	(.5)	(.3)	NA	(.4)	(.3)	(.5)	(.6)	(.5)	(.5)	NA
Percent water	75	72	75	76	75	79	78	75	76	77	78	77
Aluminum (Al)	550	870	60	1,460	710	190	320	190	520	190	70	190
Arsenic (As)	2.7	7.5	4.3	7.1	5.7	1.8	3.2	3.2	3.5	5.7	2.8	3.2
Chromium (Cr)	<1.9	<1.8	0.8	<2.0	--	<2.5	<2.1	.7	<2.1	.8	<2.4	--
Cobalt (Co)	2.2	8.1	1.1	2.3	2.2	1.0	1.6	1.3	1.7	.9	.8	1.2
Copper (Cu)	45	60	80	90	70	40	50	50	28	40	25	40
Iron (Fe)	500	770	86	420	460	360	300	180	530	220	110	260
Lead (Pb)	.2	.3	<.2	1.6	.25	<.3	<.2	.5	.5	<.4	<.2	<.4
Mercury(Hg)	.2	.5	1.9	48	1.2	.2	.2	.1	.5	.3	.4	.25
Nickel (Ni)	3.2	4.9	4.2	3.4	3.9	3.0	3.4	2.4	4.1	1.7	2.9	3.0
Selenium (Se)	--	<1.1	--	<1.2	--	--	<1.3	--	2.1	2.9	<1.4	--
Silver (Ag)	.3	.3	2.2	3.8	1.3	<.3	<.2	<.2	.6	.9	<.2	.4
Vanadium (V)	1.8	2.6	1.1	5.8	2.2	1.3	1.1	.6	1.4	<.4	.8	.95
Zinc (Zn)	77	69	53	75	70	69	80	61	84	207	60	75

[1] No crayfish were found at site 5 (Fallon).

[2] Mean length, in inches (figure 3).

along 8 mi of the Carson River beginning about 1,500 ft upstream from the Carson City sampling site. Ore tailings still exist, particularly in flood plains, along the Carson River and probably continue to erode into the river. Mercury coexists with silver in the ore tailings because it was used in the amalgamation process to separate the silver and accompanying gold from the crushed ore. Mercury contamination has been documented in the lower Carson River, especially downstream from Carson City (Van Denburgh, 1973; Cooper and others, 1985; Gustin and others, 1994). The cause of chromium, lead, and zinc enrichment in the bed-sediment sample at this site is unknown, but may be urban runoff (Driver and others, 1985) from the Carson City area. Arsenic may be enriched at the Carson City site because of a natural, downstream increase in the soil arsenic concentration (Tidball and others, 1991) or transport from upstream sources.

The Fort Churchill (site 4) bed-sediment sample was slightly enriched in aluminum and zinc, moderately enriched in arsenic, and greatly enriched in silver (fig. 4). The PCA results show that three components scored high in the Fort Churchill bed-sediment sample: Al-Fe; Zn-Cu; and Ag-Hg (fig. 2). This sample may not represent the true trace-element concentrations at this site, particularly for mercury. For example, all concentrations in Fort Churchill bed-sediment samples collected by Van Denburgh (1973), Richins and Risser (1975), and Cooper and others (1985) were 3 to 40 times higher than the bed-sediment samples collected during this present study. In the Van Denburgh and Cooper studies, bed-sediment samples were collected from the top 1 to 3 in., whereas for this current study, bed-sediment samples were collected from the top 1 in. Thus, the sample for the current study could have been recently deposited sediment from upstream erosion of soil with low mercury concentration. An extensive network of gullies was present in 1992 at a vehicle testing area upstream from the Fort Churchill site.

The Fallon (site 5) bed-sediment sample was slightly enriched in chromium, copper, lead, and zinc; and greatly enriched in arsenic, mercury, selenium, and silver (fig. 4). The PCA results show that four components scored high in the Fallon bed-sediment sample: Pb-Cr-Cu; Se-As-Hg; V; and Ag-Hg (fig. 2). Potential sources of these trace elements include lead and chromium from urban runoff (Driver and others, 1985) in the Fallon area, arsenic and selenium from irrigation drainage (Hoffman and others, 1990; Seiler, 1996), and silver and mercury from the erosion of Comstock era mill tailings before Lahontan Reservoir was created in 1916 (Gustin and others, 1994; Hoffman, 1994).

Crayfish

The trace-element analysis of crayfish showed that crayfish in the Markleeville sample (site 1) generally had the lowest trace-element concentrations and those in the Fort Churchill sample (site 4) generally had the highest (table 3). Samples from Gardnerville and Fort Churchill (sites 2 and 4) were enriched in seven trace elements (fig. 4). The Carson City crayfish sample was enriched in five trace elements. Crayfish were not found at Fallon (site 5), thus no sample was available for analysis.

The crayfish sample from Gardnerville was slightly enriched (1.1 to 1.5 times higher than Markleeville) in copper, lead, and vanadium; moderately enriched (1.6 to 2.0 times higher) in aluminum and nickel; and greatly enriched (greater than 2.0 times higher) in arsenic and mercury (fig. 4). The PCA results show that four components scored high in the crayfish sample from Gardnerville site: Fe-Al-V; As-Ni; Cu; and Pb (fig. 5). The crayfish sample from Carson City (site 3) was slightly enriched in arsenic, and nickel; moderately enriched in copper; and greatly enriched in mercury and silver (fig. 4). The PCA results show that three components scored high in the crayfish sample from Carson City: Ag-Hg; As-Ni; and Cu (fig. 5). The crayfish sample from Fort Churchill was moderately enriched in copper; and greatly enriched in aluminum, arsenic, lead, mercury, silver, and vanadium (fig. 4). The mercury concentration in the Fort Churchill

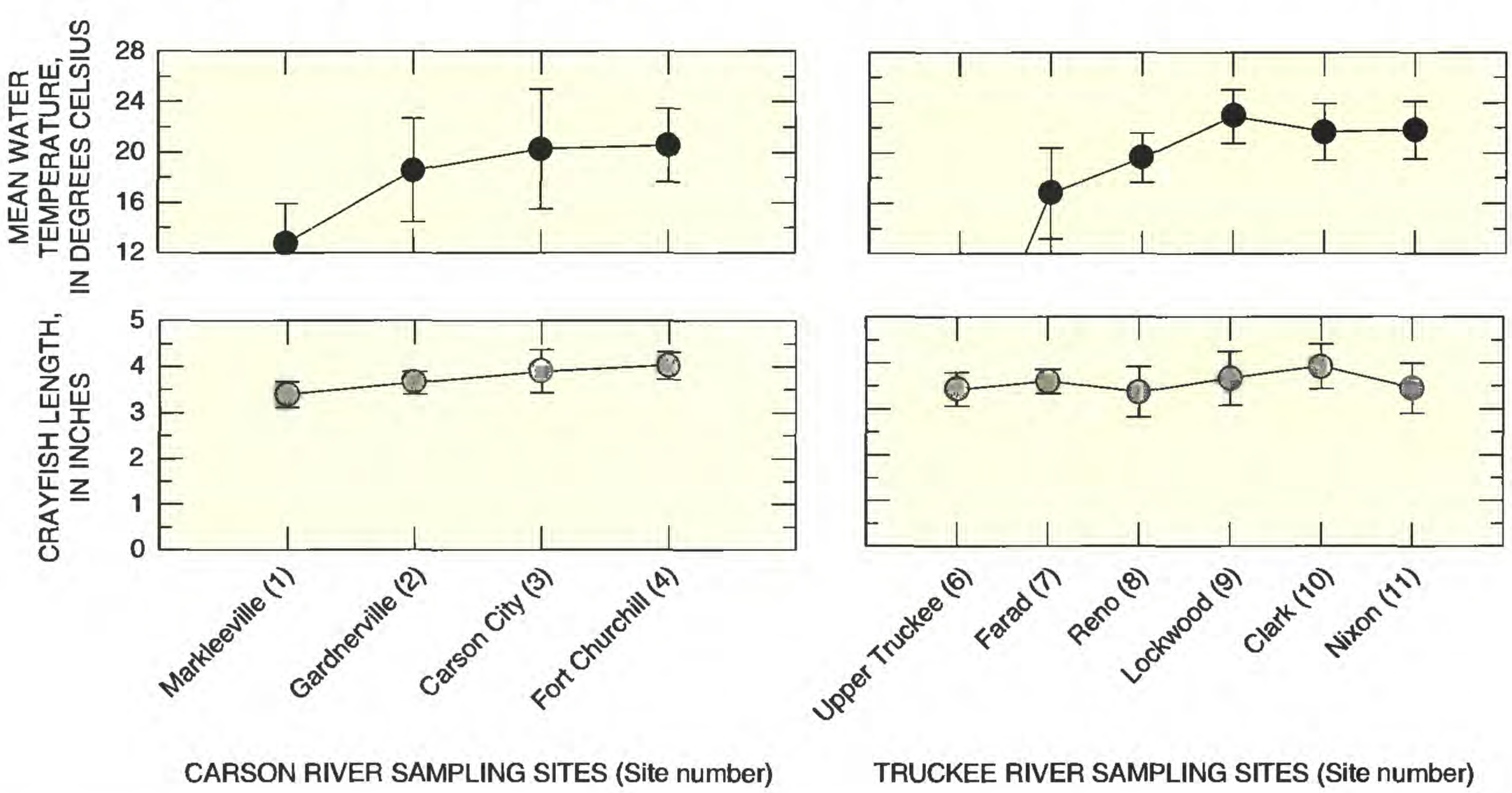

Figure 3. Relation between crayfish length and water temperature in Carson and Truckee River Basins.

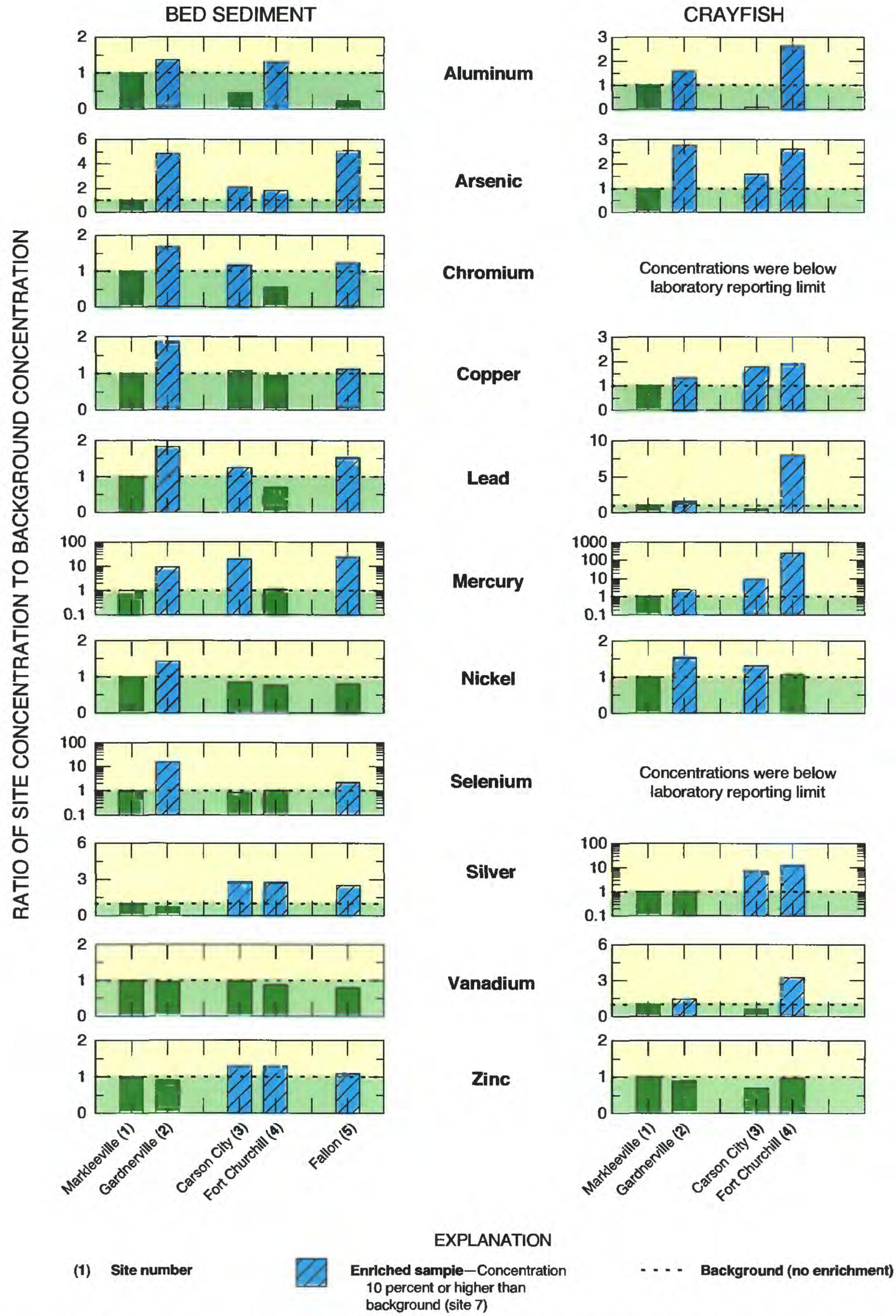

Figure 4. Comparison of trace-element concentrations in bed-sediment and crayfish samples from sites in Carson River Basin, relative to background site (East Fork Carson River near Markleeville, Calif.). Aluminum, chromium, silver, and vanadium concentrations in bed-sediment samples were adjusted for sample's total organic-carbon concentration. Crayfish were not found at Fallon (site 5).

Crayfish (*Pacifastacus leniusculus*) used in the trace element analysis of tissue. Photograph by Kenneth J. Covay, U.S. Geological Survey.

sample was 48 $\mu g/g$ (dry weight), by far the highest measured in the study (table 3). The PCA results show that six components scored high in the crayfish sample from the Fort Churchill site: Fe-Al-V; Ag-Hg; Zn; As-Ni; Cu; and Pb (fig. 5). The source or sources of trace elements in crayfish were not known because of multiple potential sources and several potential avenues of biouptake and bioaccumulation. These should be the subject of future studies.

Truckee River

Bed Sediment

Trace-element concentrations in the Truckee River bed sediments are given in table 2. Truckee River bed-sediment samples were considered enriched when the trace-element concentration was at least 10 percent greater than the concentration at the Farad, Calif., site (site 7). The bed-sediment sample from the Upper Truckee River near South Lake Tahoe, Calif. (site 6), was enriched with four trace elements (fig. 6); six trace elements were enriched in the sample at Reno, Nev. (site 8). The bed-sediment samples at Lockwood, Nev. (site 9), and Clark, Nev. (site 10), were enriched with seven trace elements. The bed-sediment sample for Truckee River at Nixon, Nev. (site 11), was enriched with three trace elements (fig. 6).

The bed-sediment sample for the Upper Truckee River (site 6) was slightly enriched (1.1 to 1.5 times higher than Farad) with vanadium, moderately enriched (1.6 to 2.0 times higher) with arsenic and lead, and greatly enriched (greater than 2.0 times higher) in selenium (fig. 6). The PCA results show that three components scored high in the Upper Truckee River bed-sediment sample: Pb- Cr-Cu; Al-Fe; and V (fig. 2). The source of lead in the Upper Truckee River bed sediment is probably the South Lake Tahoe urban area, which includes the South Lake Tahoe airport upstream from the sampling site. The source of arsenic and selenium is unknown.

The bed-sediment sample from the Reno site was moderately enriched with arsenic and copper, and greatly enriched with lead, mercury, selenium, and zinc (fig. 6). The PCA results show that three components scored high in the bed-sediment sample from the Reno site: Pb- Cr-Cu; Ni-Co; and Zn-Cu (fig. 5). The source of enriched copper, lead, mercury, and zinc concentrations at the Reno site probably is urban runoff. Streambed sediments in urban settings tend to be enriched with several trace elements, particularly lead, zinc, copper, chromium, and mercury (Driver and others, 1985; Ellis and Mustard, 1985; Licsko and Struger, 1995).

The bed-sediment sample from Lockwood was slightly enriched with copper, silver, and zinc; moderately enriched with lead; and greatly enriched with arsenic, mercury, and selenium (fig. 6). The PCA results show that the bed-sediment sample from Lockwood scored high in zinc, lead, and copper (fig. 5). Bed sediment at Lockwood probably contains urban-derived sediment, but some of the trace elements may have an additional source. Steamboat Creek, a tributary upstream from Lockwood, drains an area where ore was milled during the Comstock era, and also

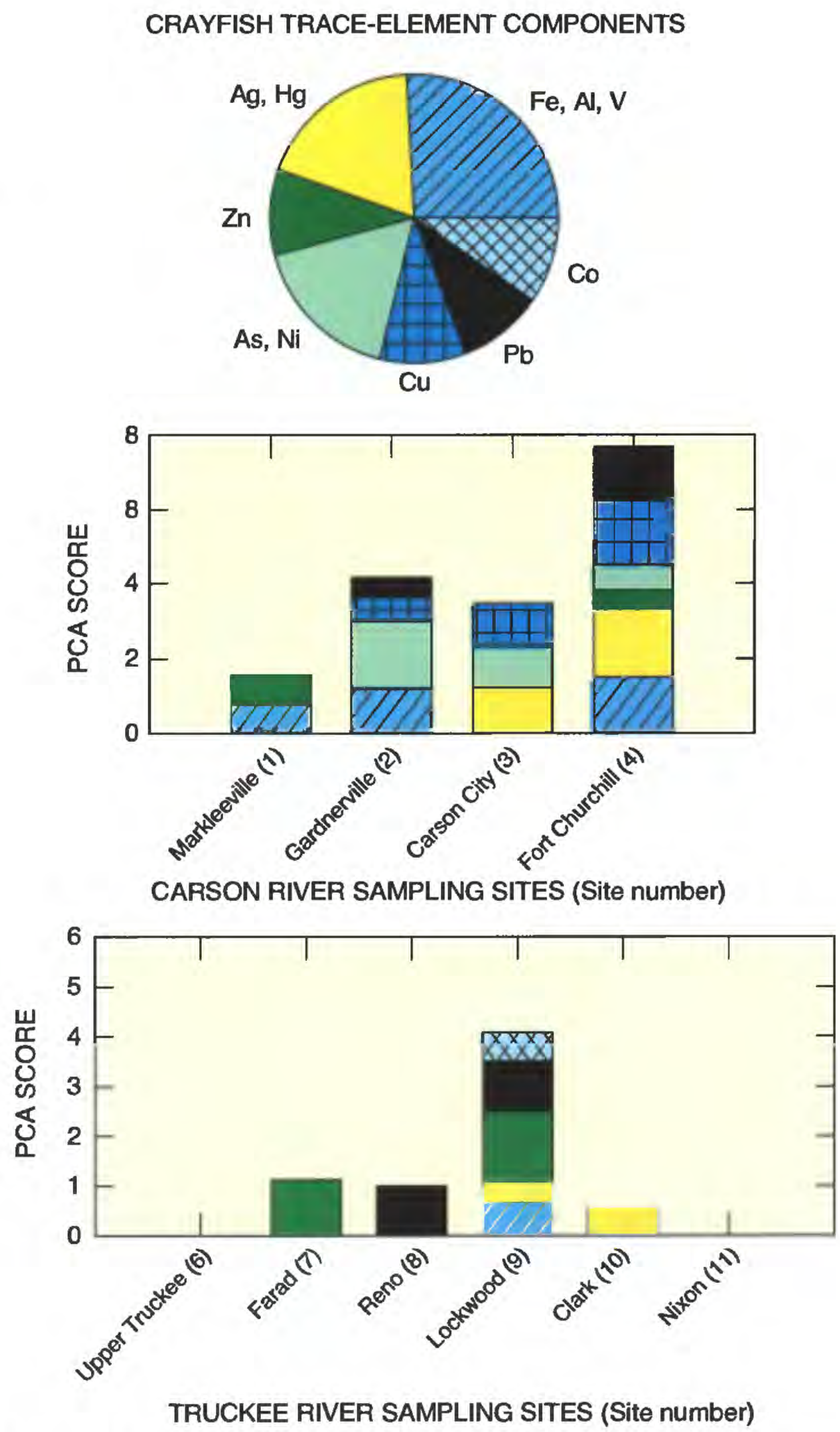

Figure 5. Trace-element components that account for 92 percent of variability in Carson and Truckee River Basin crayfish samples (pie diagram), and trace-element components that account for variability at each Carson and Truckee River Basin sampling sites (bar charts). Scores quantify a component's importance in accounting for total trace-element variability at each site.

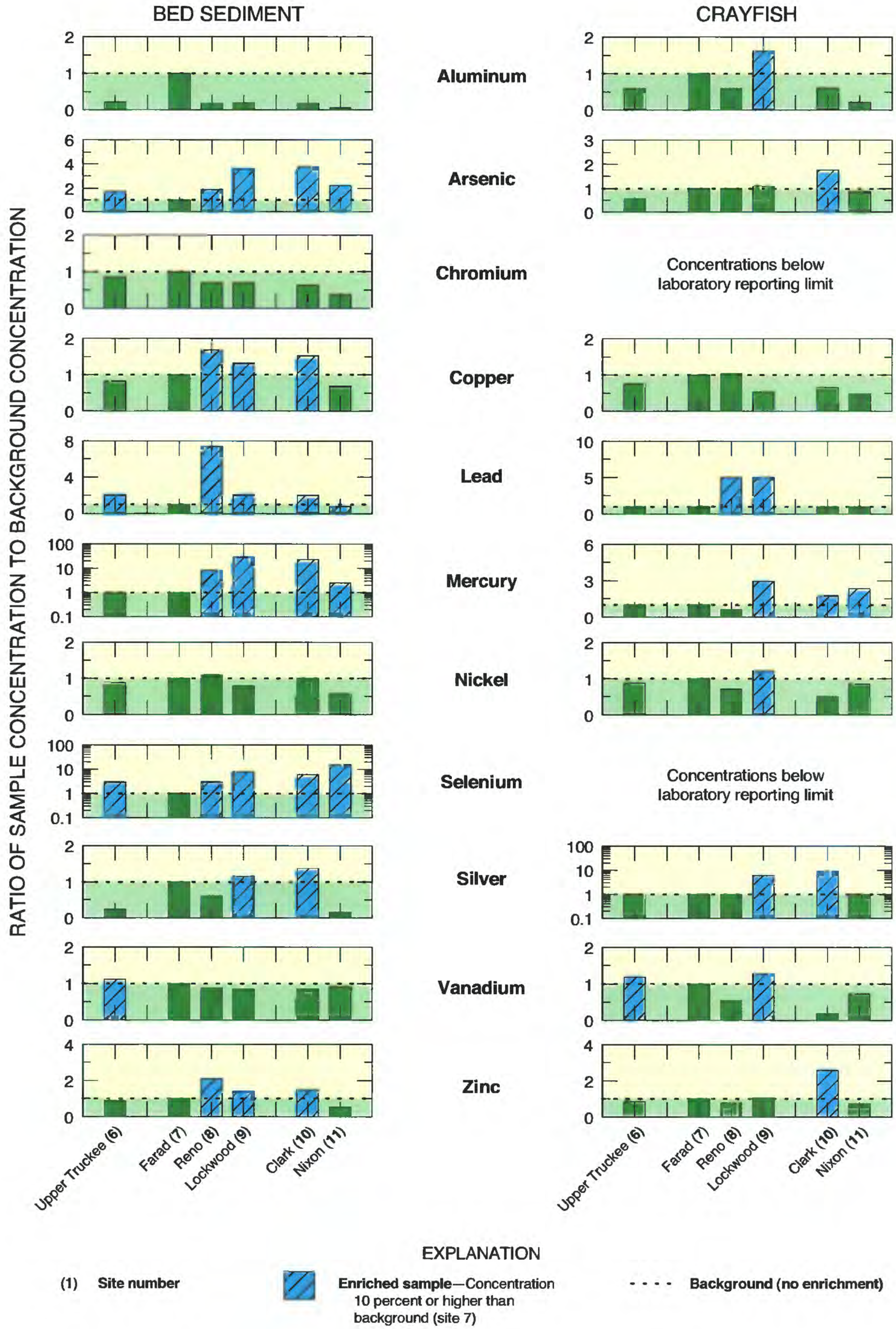

Figure 6. Comparison of trace-element concentrations in bed-sediment and crayfish samples from sites in Truckee River Basin, relative to background site (Truckee River at Farad, Calif.). Aluminum, chromium, silver, and vanadium concentrations in bed-sediment samples were adjusted for sample's total organic-carbon concentration.

receives water from an area of geothermal springs (Steamboat Springs) and tertiary-treated effluent from a large sewage plant. Water from geothermal springs can contain high amounts of arsenic and zinc, and small amounts of mercury and silver (Garside and Schilling, 1979). Forstner and Wittman (1979) state that detergents commonly contain high concentrations of arsenic. Data from Clary and others (1995) show that dissolved arsenic concentrations as high as 120 μg/L were measured in water samples from Steamboat Creek above where treated-sewage effluent is discharged. Trace elements, particularly silver, are commonly present in sewage effluent (Sanudo-Wilhelmy and Flegal, 1992). According to Forstner and Wittman (1979), sewage sludge can contain lead, zinc, and silver at concentrations 30 to 200 times greater than concentrations in crustal rock. In addition to nitrogen removal, tertiary treatment of sewage effluent also may remove phosphorus by chemical flocculation within treatment ponds. This flocculation causes particulates to precipitate out of the effluent and also may remove trace elements because they commonly are sorbed to particulates. Flocculation that continues after effluent is discharged to Steamboat Creek may be a source of the trace elements measured at Lockwood and Clark.

The bed-sediment sample from the Clark site is slightly enriched with copper, silver, and zinc; moderately enriched with lead; and greatly enriched with arsenic, mercury, and selenium (fig. 6). The PCA results show that three components scored high in the bed-sediment sample from Clark: Pb-Cr-Cu; Ni-Co; and Zn-Cu (fig. 5). The source of trace elements at Clark may be similar to the source of trace elements at Reno and Lockwood.

The bed-sediment sample from Nixon was moderately enriched with arsenic and greatly enriched with mercury and selenium (fig. 6). The PCA results show that two components scored high in the bed-sediment sample from Nixon: Se-As-Hg; and V (fig. 2). Irrigated agriculture exists upstream from the Nixon site and irrigation return flows probably enter the Truckee River above Nixon. Irrigation drainage commonly contains high amounts of arsenic and selenium (Hoffman and others, 1990; Seiler, 1996). Other sources of arsenic, mercury, and selenium may be the same as those at Lockwood and Clark.

Processing bottom sediment for analysis of trace elements, Truckee River at Reno, September 1992. Photograph by Ronald P. Collins, U.S. Geological Survey.

Crayfish

Trace-element concentrations for crayfish samples from the Truckee River are shown in table 3. Crayfish samples were considered enriched when the trace-element concentration was at least 10 percent greater than the concentration at the Farad site (site 7). Chromium and selenium concentrations in crayfish samples generally were below laboratory reporting limits.

Crayfish samples from the Upper Truckee River at South Lake Tahoe (site 6) and the Truckee River at Reno (site 8) and Nixon (site 11) were enriched with only one trace element (fig. 6). The crayfish sample from Lockwood (site 9) was enriched with six trace elements. The crayfish sample from Clark (site 10) was enriched with four trace elements.

The crayfish sample from the Upper Truckee River was slightly enriched (1.1 to 1.5 times higher than Farad) with vanadium (fig. 6). The PCA results show that no component scored high in the crayfish sample from the Upper Truckee River (site 6, fig. 5). The crayfish sample from the Reno site (site 8) was greatly enriched with lead (greater that 2.0 times higher; fig. 6); lead was the only component that scored high at the site (fig. 5).

The crayfish sample from the Lockwood (site 9) was slightly enriched with nickel and vanadium; moderately enriched with aluminum (1.6 to 2.0 times greater than Farad); and greatly enriched with lead, mercury, and silver (fig. 6). The PCA results show that five components scored high at the Lockwood site: Fe-Al-V; Ag-Hg; Zn; Pb; and Co (fig. 5).

The crayfish sample from Clark (site 10) was moderately enriched with arsenic and mercury and greatly enriched with silver and zinc (fig. 6). However, PCA results show that only one component (Ag-Hg) scored high in the Clark sample (fig. 5). The crayfish sample at Nixon (site 11) was greatly enriched with mercury (fig. 6), but PCA show that none of the components scored high enough to be considered significant at the Nixon site (fig. 5).

Comparisons Between Bed Sediment and Crayfish

Generally, those trace elements that were enriched in Carson River bed-sediment samples also were enriched in crayfish samples. Aluminum, arsenic, copper, lead, mercury, and nickel were enriched in the bed-sediment and crayfish samples from the Gardnerville site (fig. 4). Because of high laboratory detection limits, chromium and selenium concentrations were reported as less than the detection limit in crayfish samples. Arsenic, mercury, and silver were enriched in the bed-sediment and crayfish samples from the Carson City site (fig. 4). Aluminum, arsenic, and silver were enriched in bed-sediment and crayfish samples from the Fort Churchill site (fig. 4). The bed sediment sample and crayfish sample were not similarly enriched for mercury because the bed-sediment sample probably was not representative of mercury concentrations at Fort Churchill.

Generally, relations were few between trace elements in bed-sediment and crayfish samples from the Truckee River. Both types of samples from the Reno and Lockwood sites were enriched in lead (fig. 6). Both types of samples from the Lockwood site also were enriched in mercury and silver (fig. 6). Both types of samples from the Clark site were enriched in arsenic, mercury, silver, and zinc (fig. 6). Bed-sediment and crayfish samples from the Nixon site were enriched with mercury (fig. 6).

When the Carson and Truckee River bed-sediment and crayfish data were merged into one data set, a significant correlation was seen between arsenic, mercury, and silver concentrations in bed sediment and crayfish samples (*p* less than 0.001; fig. 7). The correlation suggests that these elements were either bioavailable and were bioaccumulating in crayfish or trace elements were strongly sorbing onto crayfish exoskeletons. Thus, arsenic, mercury, and silver appeared to be readily accumulated by crayfish in the study area, particularly in the Carson River. Furthermore, the arsenic, mercury,

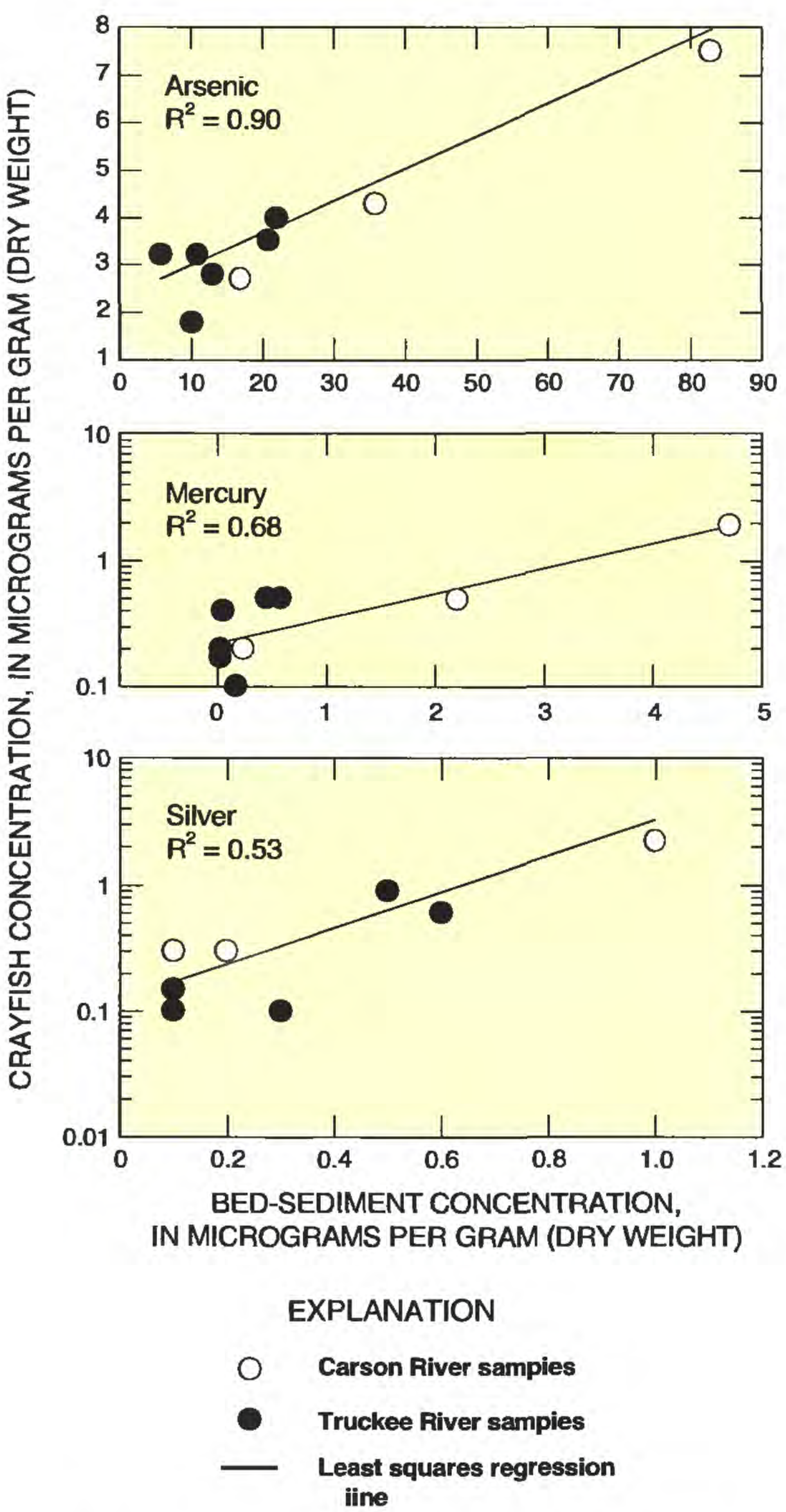

Figure 7. Relation between arsenic, mercury, and silver in bed-sediment and crayfish samples from Carson and Truckee River Basins. Data from Fort Churchill was not representative and was not used in regression analysis.

and silver concentrations in crayfish increase with increases in body length, a correlation that also was reported in studies by Stinson and Eaton (1983) and Rada and others (1986). However, in this current study, such a relation may be spurious because arsenic, mercury, and silver were higher in the bed sediments, water temperatures were higher, and crayfish were larger in the lower reaches of both rivers. Mercury accumulation by crayfish from the Carson and Truckee Rivers may be either by ingestion of mercury enriched macrophytes (Ribeyre, 1993) or facilitated diffusion through the gills (Rainbow and Dallinger, 1993).

The concentrations of lead, nickel, and zinc in crayfish samples were not consistently related to concentrations in bed sediment, nor were they accumulated in proportion to body length. Other researchers show that concentrations of zinc in *Orconectes spp.* of crayfish (Mirenda, 1986) and lead in *Procambarus Clarkii* (Pastor and others, 1988) were directly related to concentrations in water and that gills contained the highest concentrations. However, bioaccumulation of zinc appears to be biochemically regulated within narrow limits in many invertebrates including crayfish (Rainbow and Dallinger, 1993). Stinson and Eaton (1983) showed that when crayfish (*Pacifastacus leniusculus*) were exposed to lead from urban runoff, they readily accumulated it, especially in the exoskeleton. Aluminum, iron, and vanadium may be bioavailable to crayfish through food ingestion (Greger and Kautsky, 1993) and, as in bed-sediment samples in this current study, probably represent the geology in both basins. Chromium is not appreciably accumulated in the crayfish samples collected in this study. Historically, dissolved-chromium concentrations were measured in water samples from these rivers at levels only slightly higher than laboratory reporting levels (U.S. Geological Survey WATSTORE data). Hernandez and others (1986) indicate that dissolved chromium is readily accumulated by the crayfish *Procambarus clarkii*. The mechanisms facilitating bioaccumulation of trace elements in crayfish from the Carson and Truckee River Basins are not known and such identification was not an objective of this study.

SUMMARY

As part of the USGS National Water-Quality Assessment (NAWQA) Program, 11 bed-sediment samples and 10 whole crayfish samples were collected at sampling sites in the Carson and Truckee River Basins, Nevada and California, in September 1992. Samples were collected using protocols developed specifically for the NAWQA Program. Twenty-three trace elements were analyzed in each sample, but only 11 are addressed in this paper. Sites were compared to a background site to determine degree of trace-element enrichment. Data were analyzed by a factor analysis using principal components (PCA) to identify multivariable correlations among trace elements in bed sediments and crayfish samples, analyzed by Spearman's rank correlation and linear regression. To help identify relations between bed-sediment and crayfish samples, crayfish sizes were compared among sites and between basins using the Mann-Whitney U-test.

Bed sediments in the Carson and Truckee Rivers were enriched with trace elements from several possible sources including erosion of natural mineral desposits, urban runoff, erosion of mine and mill tailings, acid mine drainage, irrigation drainage, sewage effluent, and geothermal springs. Arsenic concentrations were significantly higher in the Carson River bed-sediment samples than in the Truckee River bed-sediment samples. Trace-element concentrations in crayfish samples were not statistically different between the two river basins. Crayfish readily accumulated arsenic, mercury, and silver in proportion to body length and to concentrations in bed sediments. However, crayfish were larger in the lower parts of both rivers possibly because of faster growth rates as a result of higher water temperature.

Natural mineral deposits and past mining and ore-milling practices probably have enriched the Carson River bed sediments and crayfish with several trace elements. Soil erosion and acid mine drainage from the Leviathan Mine might have enriched bed sediment in the East Fork Carson River near Gardnerville with aluminum, arsenic, chromium, copper, lead, mercury, nickel, and selenium. Additional sources of trace elements might be other small, abandoned mines and natural mineral deposits. Historical milling of gold and silver from the Comstock mining area has enriched bed sediment downstream from Carson City with mercury and silver. Arsenic and selenium in Carson River bed sediment may be related to irrigation drainage or geothermal discharge.

Urban activity may be the primary source of trace-element enrichment in Truckee River bed-sediment and crayfish samples. However, agricultural activity, historical ore milling, and geothermal discharge also may contribute trace elements to the river. Bed sediment and crayfish from the Truckee River downstream from Reno were enriched with arsenic, lead, mercury, and silver.

Regression relations were developed between arsenic, mercury, and silver concentrations in bed-sediment and crayfish samples from the Carson and Truckee Rivers. These relations were highly significant and indicate that arsenic, mercury, and silver were bioavailable and bioaccumulated in crayfish, especially in the Carson River.

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