

TRACE ELEMENTS IN BED SEDIMENTS OF THE SAN JOAQUIN RIVER AND
ITS TRIBUTARY STREAMS, CALIFORNIA, 1985

By *Daphne G. Clifton* and *Robert J. Gilliom*

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The San Joaquin Valley Drainage Program was established in mid-1984 and is a cooperative effort of the U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, California Department of Fish and Game, and California Department of Water Resources. The purposes of the Program are to investigate the problems associated with the drainage of agricultural lands in the San Joaquin Valley and to develop solutions to those problems. Consistent with these purposes, program objectives address the following key areas: (1) Public health, (2) surface- and ground-water resources, (3) agricultural productivity, and (4) fish and wildlife resources.

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CONVERSION FACTORS

For use of readers who prefer to use inch-pound units, rather than the International System (SI) units used in this report, the following conversion factors may be used:

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
cm (centimeter)	0.394	inches
ha (hectare)	2.471	acre
km (kilometer)	0.6214	mile
m (meter)	3.281	foot

Concentrations of elements in bed sediments are given in micrograms per gram (μ g/g). Micrograms per gram is equal to parts per million.

ABBREVIATIONS USED

h	hour
μ m	micrometer
<4 μ m	less than 4 micrometers
<62 μ m	less than 62 micrometers
>62 μ m	greater than 62 micrometers

TRADE NAMES

The use of brand or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

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ABSTRACT

The occurrence and distribution of trace elements in bed sediments of the San Joaquin River, California, were assessed to determine whether some elements are concentrated in the sediments which may affect water quality adversely. Bed sediments were sampled at 24 sites on the San Joaquin River and its tributary streams in October 1985.

Samples showed that the percentage of sediment less than 62 micrometers in size correlated with total organic carbon. Concentrations of elements are higher and less variable in bed sediment of less than 62-micrometer size compared to sediment samples with all size fractions. Bed sediments are coarser in tributaries originating in the Sierra Nevada compared to tributaries draining the western valley, and thus trace-element composition is different between the two groups.

Interrelations among trace elements from different stream-site groups were

examined using principal component analysis. Together, the first and second principal components account for 57 percent of the variance, and show a distinct separation between sites dominated by Coast Range and Sierra Nevada sediments. The third and fourth components together account for 21 percent of the variance and distinguish the mixed-source sediments of the intermittent upper San Joaquin River from other parts of the river system.

Elements in bed sediments of the San Joaquin River basin were similar in concentration to elements in San Joaquin Valley soils, and were well below hazardous waste criteria. Concentrations were lower than in sediments from some polluted urban rivers and were comparable to rivers in other rural agricultural areas. The results indicate that selenium and other trace elements from subsurface agricultural drains have not concentrated to hazardous levels in bed sediments of the San Joaquin River.

INTRODUCTION

High concentrations of selenium in subsurface agricultural drain water from the western San Joaquin Valley, California, have impaired waterfowl reproduction where water was impounded at Kesterson Reservoir (Ohlendorf and others, 1986). Similar concentrations, in the range of hundreds of micrograms per liter, have reduced growth and survival of fish in laboratory experiments (Hamilton and others, 1986). Previous studies have described the areal distribution of selenium and other trace elements in drain water and in shallow and deep ground water of the western San Joaquin Valley (Deverel and others, 1984; Presser and Barnes, 1984, 1985; Neil, 1986; Deverel and Millard, 1988). Tidball and others (1986a, 1986b) studied the distribution of selenium and other elements in valley soils. Subsurface drain water from about 31,000 ha of western valley farmland, some of which contains high concentrations of selenium and other dissolved elements, flows to the San Joaquin River or its tributaries (California State Water Resources Control Board, 1987). There is concern that, even after dilution in the river, selenium or other trace elements may adversely affect the water quality of the river or concentrate in the bed sediments.

The purpose of this study is to assess the occurrence and distribution of trace elements in bed sediments of the San Joaquin River and its tributaries. Trace-element concentrations in bed sediments can be indicators of potential water-quality problems. Bed-sediment samples for this study were collected from 24 sites on the San Joaquin River and its tributaries during October 7-11, 1985. Sample analyses included trace elements, major elements, organic carbon, and particle size. This study is part of a comprehensive investigation of the hydrology and geochemistry of the western San Joaquin Valley by the U.S. Geological Survey in cooperation with the San Joaquin Valley Drainage Program.

STUDY AREA

Below the headwaters of the San Joaquin River in the Sierra Nevada, the river extends 309 km from Friant Dam in the foothills, to Vernalis (fig. 1) just upstream from the tidal backwater influence of the Sacramento-San Joaquin Delta. For the first 105 km between Friant Dam and Mendota, the river generally has intermittent flow and often river water does not reach Mendota Pool near Mendota. In the next 108 km between Mendota and Stevinson, the river has perennial flow in the upper 33 km because of Delta Mendota Canal inflows, and intermittent flow along the remaining 75 km as the result of irrigation diversions. Flow in the remaining 96 km between Stevinson and Vernalis is perennial and increases downstream as tributaries, irrigation-return flow, and ground water enter the river.

This study focuses on the San Joaquin River between Mendota and Vernalis and on the tributaries to the river within that reach (fig. 1). About 0.8 million ha of irrigated agricultural land drain directly or indirectly to this reach of river (California State Water Resources Control Board, 1987). During low-flow conditions, water in the river consists mainly of irrigation-return flows (Hunter and others, 1987), surface runoff, and subsurface drain water. Surface irrigation-return flow is typically high in suspended sediments from soil erosion (California Regional Water Quality Control Board, 1977). Drain water from subsurface drainage systems in the western San Joaquin Valley is typically high in dissolved solids, boron, and commonly selenium, and low in suspended sediments (California Regional Water Quality Control Board, 1979; Deverel and others, 1984). During high-flow periods, most San Joaquin River water is runoff from the Sierra Nevada.

Valley soils consist of weathering products from either the Sierra Nevada to the east, the Coast Range to the west, or a combination of both. The Sierra Nevada is composed of igneous and metamorphic

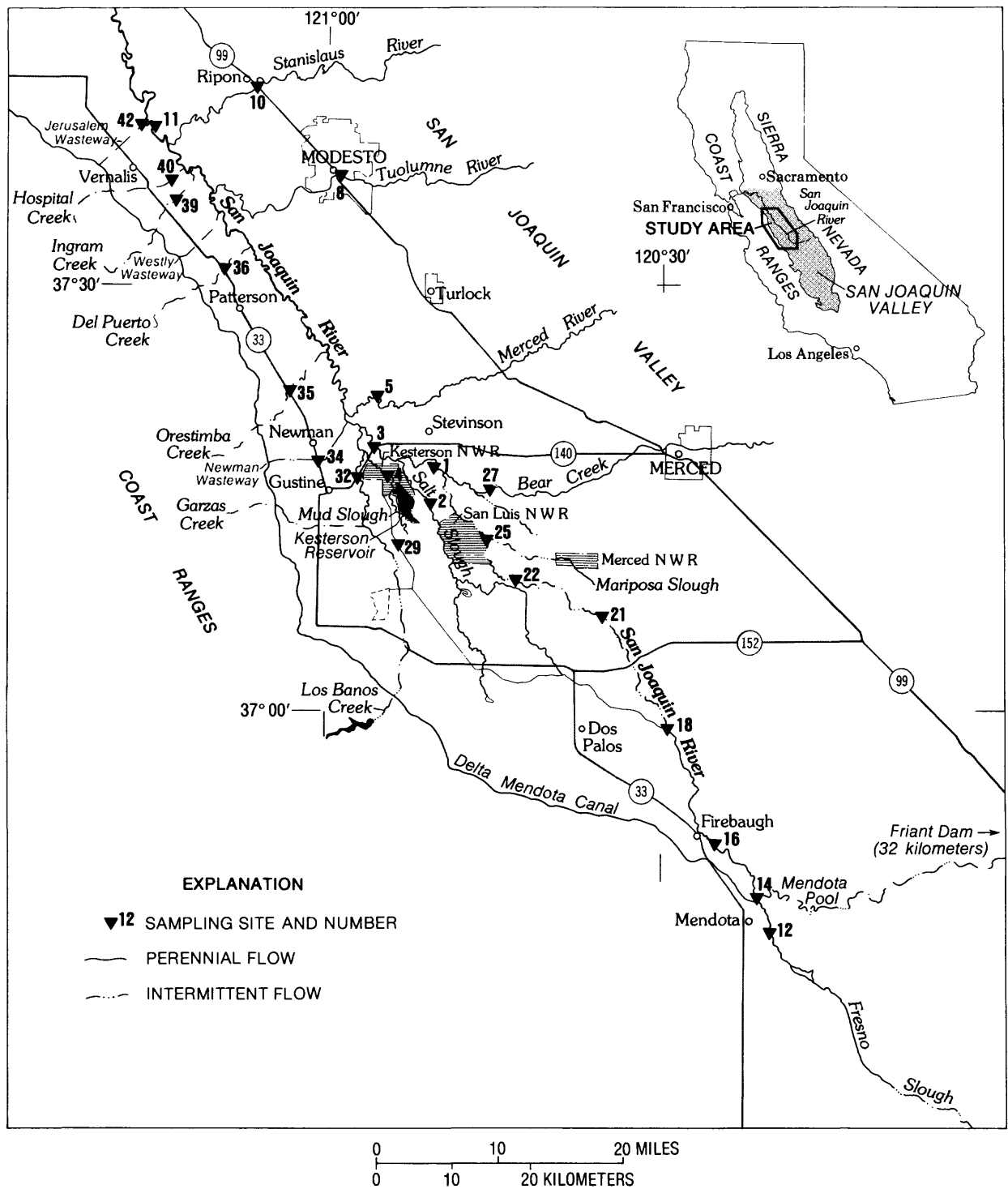


FIGURE 1.--Location of study area and sampling sites.

rocks. Sediments derived from these rocks form the alluvial fans originating in Sierra Nevada foothills and are the main component of flood-plain deposits in the San Joaquin River. River channels of Sierra Nevada tributaries consist of river deposits of gravel, sand, silt, and small amounts of clay. These sediments are coarser and more permeable than those from the Coast Range. The Coast Range is composed of gypsiferous marine shale, sandstone, and volcanic fragments, and soils of Coast Range alluvial fans generally are fine grained. Coast Range streams drain continental rocks and deposits, and the streambeds are a heterogeneous mixture of poorly sorted clay, silt, sand, and gravel (Miller and others, 1971; Page, 1983, 1986). Bed sediments in the San Joaquin River channel are a mixture from both sources, but the coarse-grained Sierra Nevada sediments predominate because of the much higher streamflow of the tributaries originating in the Sierra Nevada. Study sites on Bear Creek, Los Banos Creek, Salt Slough, and Mud Slough (fig. 1) are in flood-basin deposits consisting of clay, silt, and some sand (Page, 1986).

STUDY DESIGN AND METHODS

Sampling sites were selected at 24 locations, which represent the intermittent-flow and perennial-flow parts of the San Joaquin River, tributaries from the Sierra Nevada and Coast Range, and canals and sloughs that carry irrigation-return flow and subsurface agricultural drain water to the San Joaquin River (fig. 1). Site numbers, names, and groups used for data analysis are given in table 1. Site groups were based on geography, primary sources of water, geology, and hydrology.

The upper San Joaquin River (sites 12, 14, 16, 18, 21, 22, and 25) contained mixed sources of water and sediments during the study period, primarily water from the Delta Mendota Canal and irrigation-return flow. Bed-sediment material contained from 2 to 94 percent

of the less than 62-micrometer (<62- μ m) size fraction. The finest grained sediments occurred in pooled areas and at the intermittent-flow sites, which contained predominantly irrigation-return flow. Streamflow in the San Joaquin River below Mendota Pool (where Delta Mendota Canal water is stored) was equivalent to 15 to 16 percent of flow in the San Joaquin River near Vernalis (site 11), the farthest downstream site. Streamflow downstream of Dos Palos (site 18), after all the canal water from Mendota Pool was removed for irrigation, was equivalent to less than 0.1 percent of flow at site 11. At the time of the study, water released to the river from Mendota Pool did not reach the perennial-flow part of the San Joaquin River at Stevinson (site 1).

Although Salt and Mud Sloughs (sites 2 and 4) enter the San Joaquin River from the west, they were grouped separately because they receive more subsurface agricultural drain water than other westside tributaries. The sloughs also have coarser bed sediments (8 and 9 percent <62 μ m) compared to westside tributary streams. Streamflows in Salt and Mud Sloughs were about 7 and 2 percent of flow at Vernalis during the study period.

Streams classified as westside tributaries (sites 29, 32, 34, 35, 36, 39, 40, and 42) primarily originate from small valleys at the foot of the Coast Range. Except during high runoff events, these streams consist mainly of intermittent irrigation-return flow, overflow water from the Delta Mendota Canal, and, in some cases, a small quantity of subsurface drain water. Streamflow during the sampling period in individual streams of this group ranged from less than 0.1 to 3.8 percent of streamflow at Vernalis. Bed sediments consisted of 14 to 72 percent in the <62- μ m size fraction.

The four eastside tributaries (sites 5, 8, 10, and 27) originate in the Sierra Nevada and contain primarily coarse bed sediments (less than 1 percent <62 μ m). These tributaries have the highest flows compared to other tributaries--each

TABLE 1.--Selected characteristics of site groups used for data analysis
[Streamflow data collected September 23-27, 1985; bed-sediment data collected October 7-11, 1985;
do., Do., ditto; <, less than; μ m, micrometer]

Site No.	Site name	Stream-flow (as percent of flow at Vernalis)	Type of streamflow	<62- μ m size fraction of bed sediments (as percent of sample)	Geologic sources of bed sediments	Primary source of water at the time of the study
Upper San Joaquin River and Tributaries (Site group 1)						
12	Fresno Slough near State Highway 180.	<0.1	Intermittent	85	Sierra Nevada and Coast Range	Delta Mendota Canal backwater
14	San Joaquin River below Mendota Pool.	16	Perennial	39	do.	Delta Mendota Canal
16	San Joaquin River near Firebaugh.	15	do.	2	do.	Do.
18	San Joaquin River near Dos Palos.	.3	Intermittent	2	do.	Do.
21	San Joaquin River near WA Bridge.	<.1	do.	67	do.	Return flow
22	San Joaquin River near Turner Island.	<.1	do.	93	do.	Do.
25	Mariposa Slough near San Joaquin River.	.4	do.	94	do.	Do.
Salt and Mud Sloughs (Site group 2)						
2	Salt Slough at State Highway 165.	6.8	Perennial	9	Sierra Nevada and Coast Range	Return flow, subsurface drains
4	Mud Slough near Gustine.	1.6	do.	8	do.	Do.
Westside Tributaries (Site group 3)						
29	Santa Fe Canal.....	0.5	Intermittent	50	Coast Range	Return flow, Delta Mendota Canal overflow
32	Los Banos Creek.....	<.1	do.	41	do.	Return flow
34	Newman Wasteway.....	.8	do.	41	do.	Return flow, Delta Mendota Canal overflow
35	Orestimba Creek.....	3.8	do.	15	do.	Return flow
36	Del Puerto Creek.....	<.1	do.	16	do.	Do.
39	Ingram Creek.....	<.1	do.	14	do.	Do.
40	Hospital Creek.....	.4	do.	56	do.	Do.
42	Jerusalem Wasteway...	.2	do.	72	do.	Return flow, Delta Mendota Canal overflow
Eastside Tributaries (Site group 4)						
5	Merced River.....	12	Perennial	<1	Sierra Nevada	Sierra Nevada
8	Tuolumne River.....	11	do.	<1	do.	Do.
10	Stanislaus River.....	23	do.	<1	do.	Do.
27	Bear Creek.....	13	Intermittent	<1	do.	Do.
Lower San Joaquin River (Site group 5)						
1	San Joaquin River near Stevinson.	13	Perennial	1	Sierra Nevada and Coast Range	Sierra Nevada, return flow
3	San Joaquin River at Fremont Ford.	22	do.	4	do.	Do.
11	San Joaquin River near Vernalis.	100	do.	<1	do.	Do.

accounting for 11 to 23 percent of flow of the San Joaquin River at Vernalis during the study.

The lower San Joaquin River (sites 1, 3, and 11) has perennial flow that is greatly affected by the hydrology of the dominant eastside tributaries. Bed sediments in the lower San Joaquin River were among the coarsest compared to the other site groups and ranged from less than 1 to 4 percent <62- μ m material.

Sample Collection

The sampling approach at each site was designed to yield a composite bed-sediment sample representative of a stream reach about 10 to 30 m in length. All samples were collected from a depth interval of 0 to 6 cm in the bed sediments. When a stream was wadeable, samples were collected from at least a 3 \times 4 sample grid in the area of the reach (some grids included up to 20 or 30 samples) using stainless steel BMH-53 (Guy and Norman, 1970) or PVC-plastic core samplers. Samples from deep-pooled reaches were collected with K.B.-type stainless steel core samplers with plastic inserts (Greenson and others, 1977); these samplers can be easily lowered from bridges or other structures. At sites where the streamflow was too deep or swift to sample either by wading or with core samplers, BM-60 bed-sediment samplers (Guy and Norman, 1970) with stainless steel buckets were used to collect 5 to 10 samples from cross sections on the upstream and downstream side of the bridge. Prior to use at each sampling site, all equipment used for sampling bed sediments for total trace-element analysis was washed withalconox detergent, rinsed with 5 percent hydrochloric acid then distilled water, and followed by a thorough rinse in native water. Plastic materials were not used for collection of samples for carbon analyses, and all equipment used for carbon samples was rinsed with acetone instead of hydrochloric acid.

Samples were composited in plastic buckets and, after thorough mixing with a plastic spatula, whole (unsieved) subsamples for total-element and particle-size analyses were collected. The remainder of the sample was sieved in the field (using native water collected just above the streambed) through a 62- μ m mesh-size plastic sieve (62 μ m is the standard sand-silt break in particle-size analyses). Samples were sieved prior to analysis because trace elements tend to be associated with finer sediments (Horowitz, 1984), and it is a means of standardizing samples among diverse sites. Samples for carbon analyses were composited and sieved using stainless steel equipment. The <62- μ m particles were allowed to settle 12 h or more, then the sieve water was siphoned off prior to shipment of chilled sediment residues.

The distribution of primary and duplicate analyses of different types of bed-sediment samples collected from the study sites is shown in table 2. Of samples from the 24 sites, 22 contained sufficient <62- μ m sediment for total-element analysis; sites 10 and 11 did not. Whole samples from 14 sites, including sites 10 and 11, also were analyzed. At six sites, the >62- μ m size fraction, the whole sample, as well as sieve wash water were analyzed in addition to the <62- μ m size fraction. Five samples, including three of <62- μ m sediments and two whole samples, were split for duplicate element analysis, and five samples were split for duplicate carbon analyses.

Laboratory Analyses

Samples for element determination were analyzed in the U.S. Geological Survey laboratory in Denver by Paul Briggs and David Fey. Sample aliquots were measured for percent moisture, air-dried, ground, and homogenized. Analysis of most of the elements involved digestion in strong acids (HF, HCl, HNO₃, HClO₄) prior to inductively coupled plasma (ICP) analysis coupled with atomic emission spectroscopy (Crock and others, 1983).

TABLE 2.--Distribution of primary and duplicate analyses among types of bed-sediment samples

Site No.	Primary analyses of elements and total organic carbon			Duplicate analyses			
				Elements		Total organic carbon	
	<62 μ m	>62 μ m	Whole	<62 μ m	Whole	<62 μ m	Whole
1	x	--	x	--	--	--	x
2	x	x	x	--	--	--	x
3	x	--	--	--	--	--	--
4	x	--	x	--	--	--	--
5	x	x	x	--	--	--	x
8	x	--	x	--	x	--	--
10	--	--	x	--	--	--	--
11	--	--	x	--	--	--	--
12	x	--	--	--	--	--	--
14	x	x	x	--	x	--	--
16	x	--	--	--	--	--	--
18	x	--	x	--	--	--	--
21	x	--	x	--	--	--	--
22	x	x	x	--	--	--	--
25	x	x	x	x	--	--	--
27	x	--	x	--	--	--	--
29	x	--	--	--	--	--	--
32	x	--	--	--	--	--	--
34	x	--	--	--	--	--	--
35	x	--	--	--	--	--	--
36	x	x	x	--	--	--	--
39	x	--	--	x	--	x	--
40	x	--	--	--	--	--	--
42	x	--	--	x	--	x	--

Major elements analyzed were aluminum, calcium, iron, magnesium, phosphorus, potassium, sodium, sulfur, and titanium. Trace elements analyzed were barium, beryllium, bismuth, cadmium, cerium, chromium, cobalt, copper, europium, gallium, gold, holmium, lanthanum, lead, lithium, manganese, molybdenum, neodymium, nickel, scandium, silver, strontium, tantalum, thorium, tin, uranium, vanadium, ytterbium, yttrium, and zinc. Selenium and arsenic were determined by hydride generation-atomic absorption spectrometry after digestion in strong acids (HF, HCl, HNO₃, H₂SO₄) (Crock and

Lichte, 1982; Briggs and Crock, 1986). A cold vapor, atomic absorption procedure was used for mercury determination after digestion in a Na₂CrO₄/HNO₃ solution (Crock and Kennedy, 1986). Total organic carbon (TOC) in bed sediment was determined by the difference of total carbon (measured by oxidizing the sample in an induction furnace) and total inorganic carbon (TIC) (measured by treating a sample with acid, heating it, and measuring the amount of carbon dioxide evolved) (Wershaw and others, 1987). Standard reference samples were used for quality control.

For all major and trace elements, analyses of duplicate field samples were not significantly different ($\alpha=0.05$). Results of duplicate analyses are listed in tables 10 and 11 (at the back of report). The standard deviation of laboratory analyses of the inorganic constituents generally is less than 5 percent (Crock and Lichte, 1982; Crock and others, 1983; Briggs and Crock, 1986; and Crock and Kennedy, 1986).

Dry-weight concentrations of elements in suspension in washwater remaining after sieving and settling for 12 h or more were five to seven orders of magnitude lower than concentrations in bed sediments. This indicates that the time period (12 h or more) allowed for settling the <62- μ m particles from the slurry created during the sieving process was adequate, and loss from bed sediments in the remaining washwater was insignificant.

Particle-size analyses were done by the U.S. Geological Survey sediment laboratory in Salinas, California. The particle-size distribution of the <62- μ m size fraction of bed sediments was determined from the hydraulic properties of the particles and their fall velocity using the visual accumulation tube-pipette method. The >62- μ m size fraction was determined using sieve analysis (Guy, 1977).

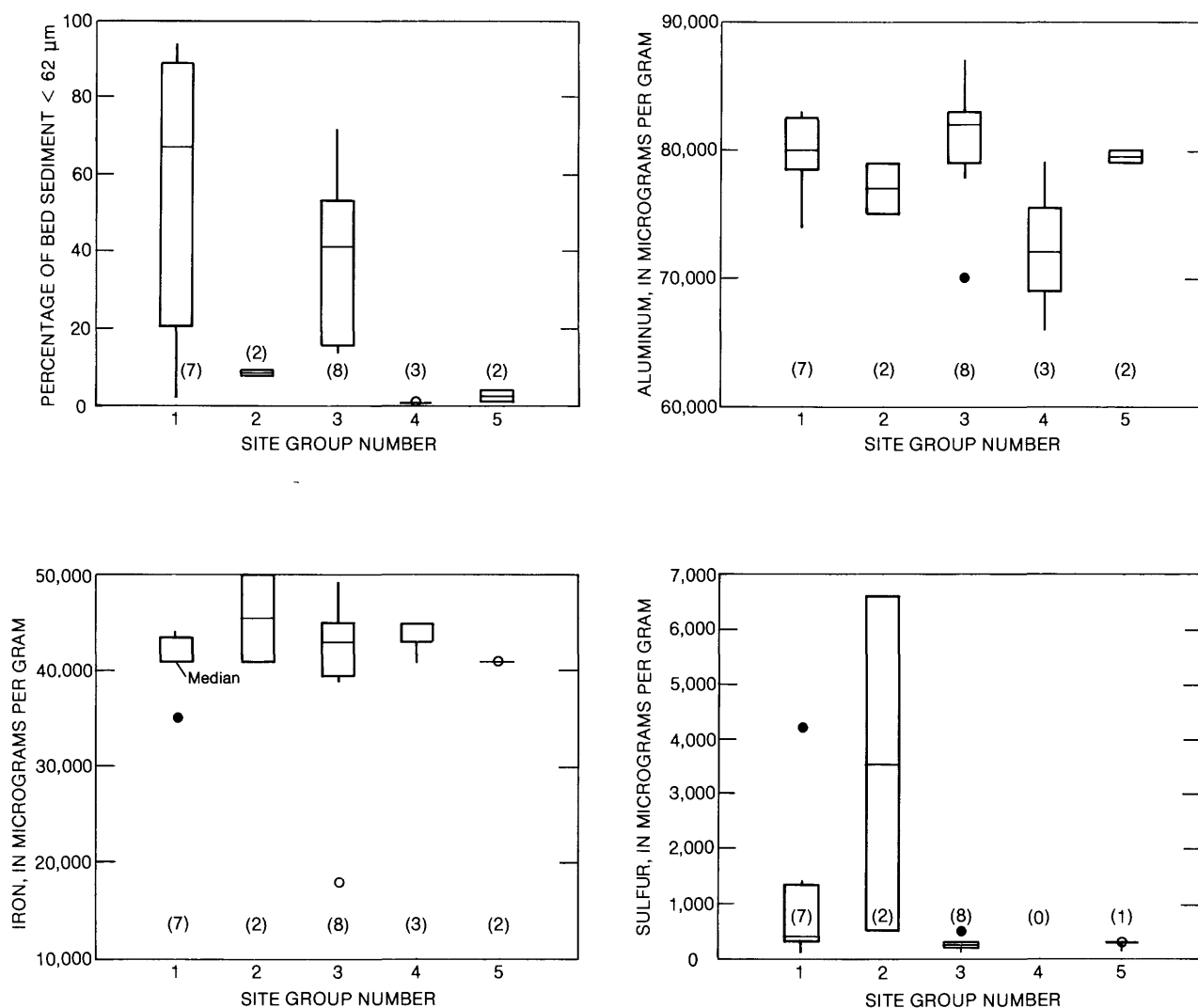
CONCENTRATIONS AND DISTRIBUTION OF TRACE ELEMENTS

Concentrations of trace elements, major elements, and total carbon in the <62- μ m bed sediments are summarized in table 3 for the 22 sites at which it was possible to collect enough <62- μ m sediments for chemical analysis. Concentrations of selected elements are summarized by site groups in figure 2. Tables 12 to 14 (at the back of report) list bed-sediment data for all sites and sample types.


TABLE 3.--Summary of concentrations of elements in <62- μ m bed sediments from the 22 sites sampled

[Other elements were analyzed for but not detected and are given at the end of this table. <, less than; μ m, micrometer; μ g/g, micrograms per gram]

Constituent	Minimum	Median	Maximum
<u>Physical characteristics (percent)</u>			
<62- μ m grain size.	<1	15.5	94
<u>Major elements (μg/g)</u>			
Aluminum.....	66,000	79,500	89,000
Calcium.....	10,000	19,000	32,000
Iron.....	18,000	41,500	50,000
Magnesium....	5,400	14,500	25,000
Phosphorus...	5,000	800	1,300
Potassium....	12,000	18,000	23,000
Sodium.....	3,000	14,500	23,000
Sulfur.....	100	300	6,600
Titanium.....	2,300	3,900	4,800
<u>Trace elements (μg/g)</u>			
Arsenic.....	5.4	9.15	16
Barium.....	640	755	990
Beryllium....	1	1	2
Cadmium.....	<2	<2	15
Cerium.....	41	48.5	73
Chromium.....	22	97.5	180
Cobalt.....	11	16	30
Copper.....	8	38	560
Gallium.....	13	19	20
Lanthanum....	23	29.5	38
Lead.....	15	20	790
Lithium.....	16	51	63
Manganese....	620	920	4,400
Mercury.....	.05	.08	.40
Molybdenum...	<2	<2	3
Neodymium....	19	25	30
Nickel.....	22	69	120
Scandium.....	5	13	17
Selenium.....	<.2	.5	1.5
Strontium....	190	290	440
Tin.....	<20	<20	90
Thorium.....	8	13	19
Vanadium.....	44	110	140
Ytterbium....	1	2	3
Yttrium.....	14	17	22
Zinc.....	34	110	230
Carbon, organic, total.	2,100	9,600	29,000
Carbon, inorganic, total.	<100	250	8,000
<u>Other elements analyzed but not detected</u>			
Element	Detection limit (μ g/g)	Element	Detection limit (μ g/g)
Bismuth.....	<10	Silver.....	<2
Europium.....	<2	Tantalum....	<40
Gold.....	<8	Uranium.....	<100
Holmium.....	<4		



EXPLANATION

-  Median
 Boxes represent the middle 50 percent of data.
 Lines extending from boxes represent range of data, excluding outliers
 ● Values are more than 1.5 times the interquartile range from the top or bottom of the rectangle.
 ○ Values are more than 1.0 times the interquartile range from the top or bottom of the rectangle.
 (4) Numbers in parentheses indicate number of observations in each site group.

SITE GROUP	NAME
1	Upper San Joaquin River
2	Salt and Mud Sloughs
3	Westside tributaries
4	Eastside tributaries
5	Lower San Joaquin River

FIGURE 2.--Distribution of < 62- μm bed sediments and concentrations of selected elements in < 62- μm bed sediments by site groups.

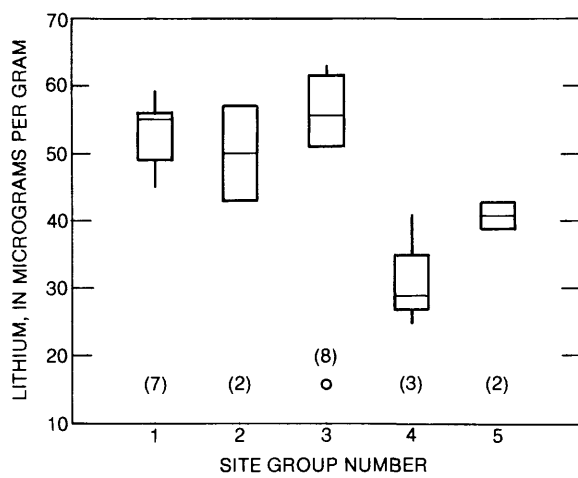
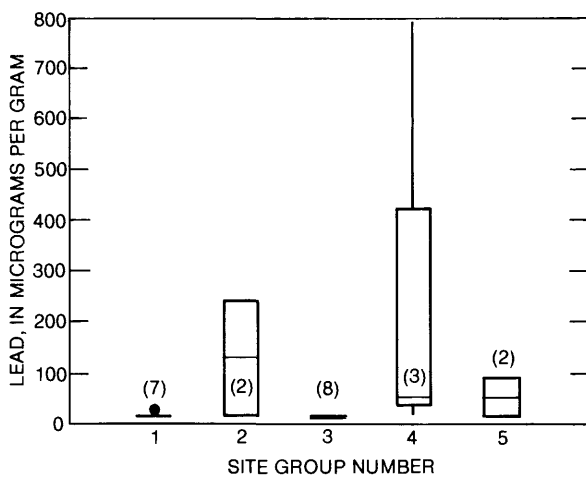
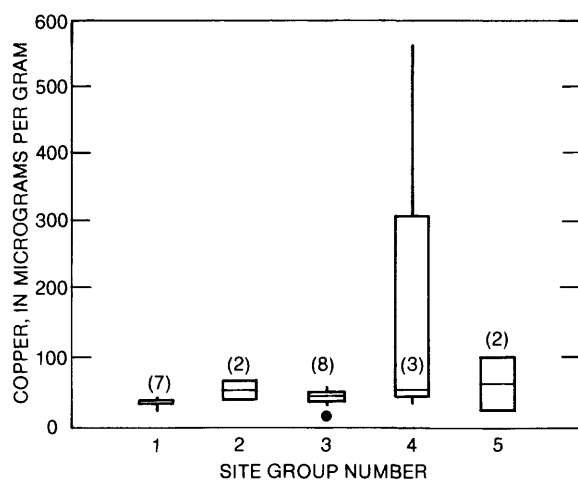
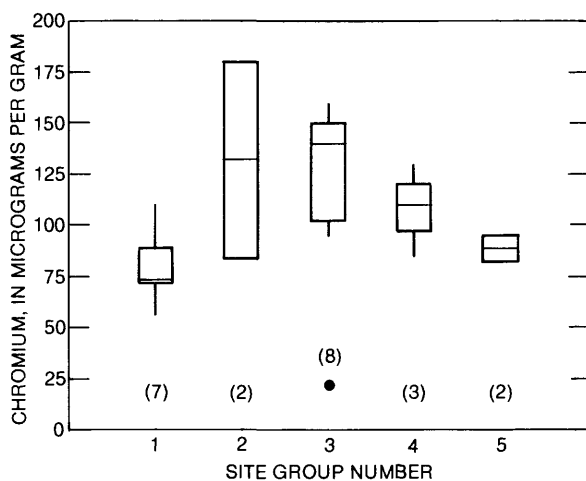
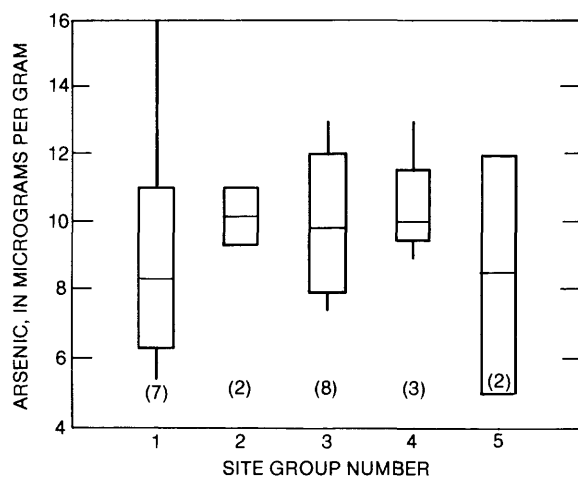
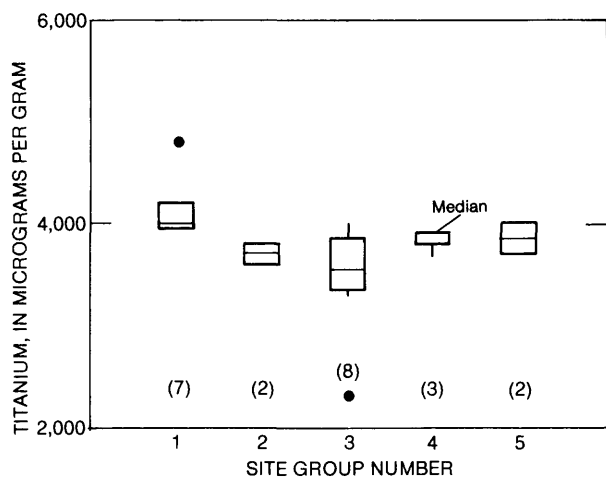


FIGURE 2.--Distribution of < 62-µm bed sediments and concentrations of selected elements in < 62-µm bed sediments by site groups --Continued.

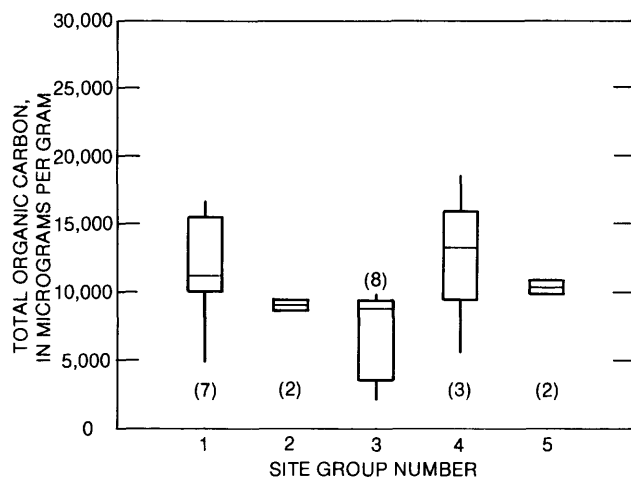
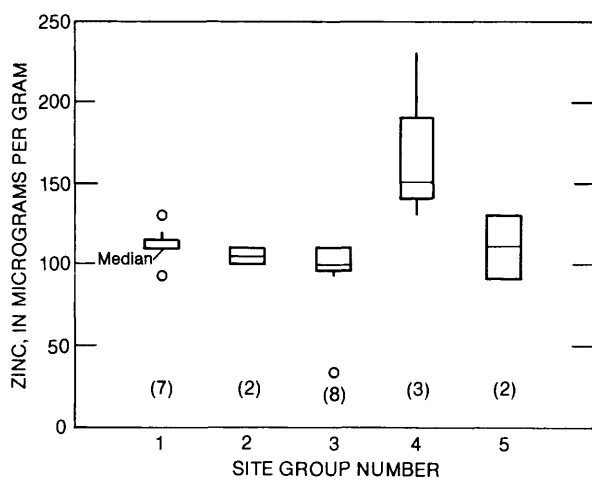
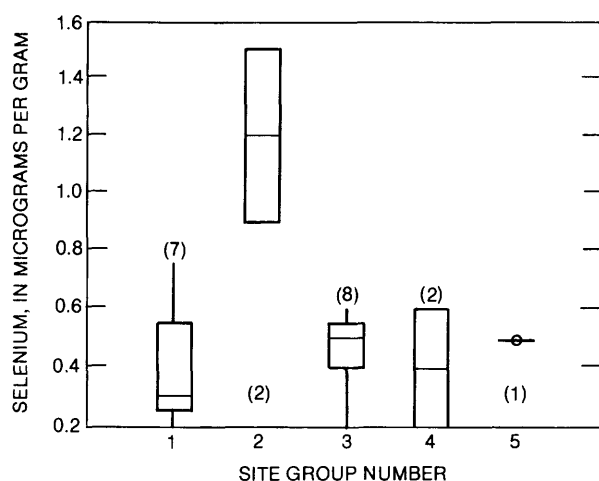
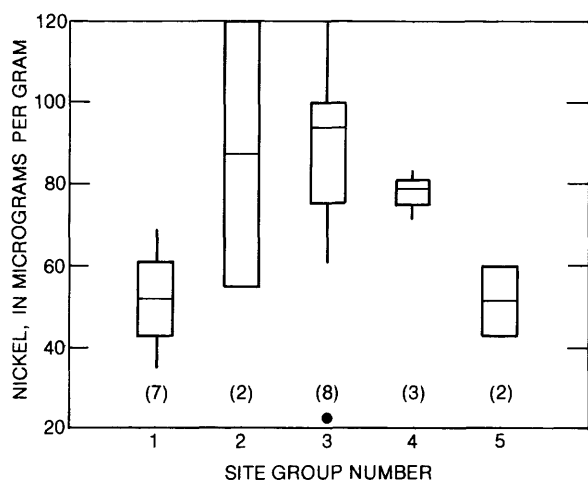
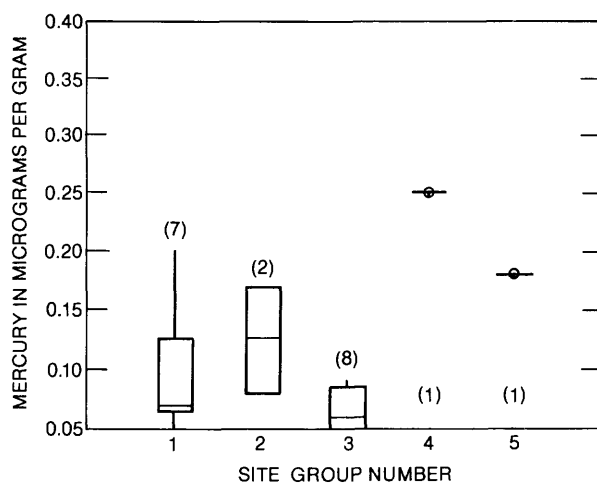
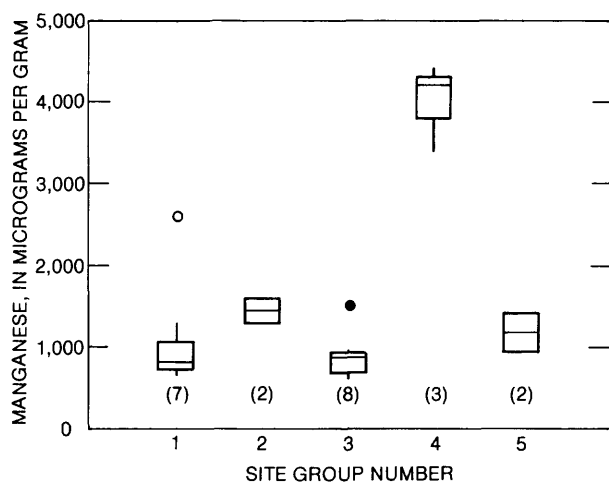


FIGURE 2.--Distribution of < 62- μ m bed sediments and concentrations of selected elements in < 62- μ m bed sediments by site groups--Continued.

Effects of Particle Size and Organic Carbon

This study focused on the <62- μ m size fraction of bed sediments for element analyses and assessment of areal distribution because the greatest concentration of most trace elements are usually associated with the clay- and silt-sized particles, which have the greatest surface area (Salomons and Forstner, 1984; Horowitz, 1986). Analysis of the <62- μ m size fraction is a means of standardizing for site comparisons.

The abundance of organic matter in bed sediments is another key factor that affects trace-element concentrations. Many elements, such as cadmium, chromium, copper, iron, lead, manganese, molybdenum, nickel, and zinc, tend to concentrate in organic coatings on sediment particles (Horowitz, 1984; Salomons and Forstner, 1984). However, a combination of low organic carbon content (0.02 to 2.77 percent) and a high correlation ($r^2=0.91$) between organic carbon and the <62- μ m size fraction made it difficult to distinguish the effect of organic matter content from the effect of particle-size on element distribution in San Joaquin River bed sediments. If the organic matter is present as coatings on particles, a high positive correlation would be expected between organic carbon and the increasing proportion of material with the greatest surface area.

Trace-element concentrations generally were higher and less variable in the <62- μ m size fraction than in larger size fractions. At six sites where trace elements were determined in <62- μ m and >62- μ m size fractions and whole sediments (table 2), median concentrations of most elements were highest in the <62- μ m fraction (table 4). Results for these six sites, plus eight additional sites for which whole-sediment samples were analyzed (table 2), showed that aluminum, arsenic, copper, iron, lithium, magnesium, mercury, phosphorus, selenium,

TABLE 4.--Comparison of median element concentrations in <62- μ m and >62- μ m size fractions, and in whole bed sediments from six sites

[The six sites are 2, 5, 14, 22, 25, and 36; see table 1 for site names. <, less than; μ m, micrometer; μ g/g, micrograms per gram]

Element	Median concentration		
	<62 μ m	>62 μ m	Whole
Major elements (μg/g)			
Aluminum.....	76,700	76,500	77,500
Calcium.....	21,300	20,700	21,500
Iron.....	37,300	28,800	33,000
Magnesium.....	11,900	9,600	12,000
Phosphorus.....	8,170	7,170	6,670
Potassium.....	17,200	20,000	17,700
Sodium.....	17,000	21,200	19,000
Sulfur.....	300	270	<100
Titanium.....	3,720	2,930	3,480
Trace elements (μg/g)			
Arsenic.....	8.25	5.23	5.05
Barium.....	778	780	762
Beryllium.....	1.2	<1	1.2
Cadmium.....	<2	<2	<2
Cerium.....	48.2	38.5	44.5
Chromium.....	72.7	44.8	64.2
Cobalt.....	14.5	11.5	14.5
Copper.....	34	20.5	27.8
Gallium.....	17	17.2	17
Lanthanum.....	29.5	24.2	27.3
Lead.....	22	20.2	19.3
Lithium.....	41.2	31.5	36.3
Manganese.....	1,610	943	857
Mercury.....	.08	.03	0.02
Molybdenum.....	<2	<2	<2
Neodymium.....	24.7	21.7	24.8
Nickel.....	47.7	30.0	58.7
Scandium.....	11.5	8.2	10.7
Selenium.....	.3	.15	.1
Strontium.....	288	318	290
Thorium.....	13.8	10	12.3
Tin.....	<20	<20	<20
Vanadium.....	97.5	72.3	88.3
Ytterbium.....	1.8	1.6	1.8
Yttrium.....	15.3	12.5	15.2
Zinc.....	113	70.7	82.5
Carbon, organic, total.	10,900	9,150	7,220

sulfur, titanium, total organic carbon, and the percent <4- μm size fraction, were correlated with the fraction of sample material <62 μm . For 12 of these 14 sites (table 2), whole and <62- μm sediments were analyzed. Concentrations of 28 of the 33 elements analyzed in whole sediments showed greater variability compared to concentrations in <62- μm sediments from the same 12 sites, as determined using the coefficient of variation (geometric deviation/geometric mean). Only barium, copper, lead, manganese, and sodium concentrations were more variable in the <62- μm size fraction. The median coefficient of variation for elements in whole sediments (0.468 $\mu\text{g/g}$) was nearly double that for the same elements in <62- μm sediments (0.238 $\mu\text{g/g}$), indicating the effectiveness of using the <62- μm size fraction to reduce variability of element concentrations between sites.

The median percentage of the <62- μm size fraction in bed sediments was much lower in eastside tributaries (less than 1 percent), the lower San Joaquin River (1 percent), and Salt and Mud Sloughs (8.5 percent), when compared to westside tributaries (41 percent) and the upper San Joaquin River (67 percent) (table 1, fig. 2). Analysis of variance showed that the proportion of <62- μm particles was significantly different between the eastside and westside tributaries ($P < 0.05$); the Mann-Whitney test also showed a significant difference between medians ($P < 0.05$). But there was no significant difference between either of these site groups and the sites on the upper and lower San Joaquin River, and Salt and Mud Sloughs, which contain a variable mixture of sediment derived from eastside and westside sources.

Standardizing trace-element concentrations by analyzing only the <62- μm particles decreases the effect of these physical differences between bed sediments so that effects of the differences in geology, hydrology, and possibly land use on trace-element composition can better be examined. In addition, trace-element loads to the San Joaquin River

and transport in the river are mainly in the <62- μm fraction of suspended sediments; between 80 and 90 percent of suspended sediments in the eastside tributaries, and 90 and 100 percent in the lower San Joaquin River and sloughs are <62 μm during most of the year (Shelton and Miller, 1988).

Abundance of Trace Elements

Most elements that were analyzed for in this study occurred at detectable concentrations, although there is considerable variability in abundance among elements (table 3). Because of their low concentrations, high detection limits, or both, bismuth, europium, gold, holmium, silver, tantalum, and uranium were not detected in any of the bed-sediment samples.

Chromium, copper, lithium, manganese, nickel, and zinc are among the more abundant trace elements that also have been measured in river water. Except for lithium, these elements tend to be associated mainly with particulate matter in water (table 5). In contrast, arsenic, molybdenum, and selenium are among the least abundant elements in bed sediments and occur mainly in dissolved forms in river water (table 5).

The relative similarity of elemental concentrations in bed sediments in different parts of the river system, the overall variability in concentrations, and the small number of sites in each site group, result in few clear distinctions between site groups based on concentrations of individual elements (fig. 2).

Comparison of site groups 1 through 4, which represent tributaries from different parts of the drainage system to the lower river, shows clear distinctions between site groups only for lithium, manganese, selenium, and zinc. Lithium is notably lower in <62- μm sediments from eastside tributaries compared to the other three groups, and manganese and

TABLE 5.--*Partitioning of elements in San Joaquin River water compared to concentrations in <62- μ m bed sediments*

[The proportion of elements in dissolved forms are medians of the ratios of dissolved to total recoverable concentrations at the 11 main sites in the San Joaquin River Study, June 1985 - January 1986. <, less than; μ m, micrometer; μ g/g, micrograms per gram]

Element	Proportion in dissolved forms (percent)	Median <62 μ m bed-sediment concentration (μ g/g) (22 sites)
<u>Elements that occur mainly in dissolved phase</u>		
Arsenic.....	75	9.15
Lithium.....	85	51
Molybdenum....	100	<2
Selenium.....	100	0.5
<u>Elements that occur mainly in particulate phase</u>		
Aluminum.....	0.6	79,500
Chromium.....	4.2	97.5
Copper.....	25	38
Iron.....	1.0	41,500
Manganese.....	24	920
Nickel.....	21	69
Zinc.....	37	110

zinc are higher. Thus, the eastside tributaries, which have bed sediments derived solely from Sierra Nevada sources, typically have low lithium and high manganese and zinc in the <62- μ m size fraction. Selenium is distinctly higher in <62- μ m bed sediments from Salt and Mud Sloughs than it is for any other site group. This corresponds to the higher levels of selenium measured in the water at those sites as well.

Interrelations Among Trace Elements and Their Areal Distribution

Interrelations among trace elements were examined using principal component analysis. Principal component analysis expresses the total variance for a group of variables in terms of principal components, which are linear combinations of the original variables. Each principal component explains a part of the total variance and each original variable is related to each principal component to different degrees. Generally, the first

few principal components explain most of the total variance and, sometimes, a combination of only a few of the total number of variables dominates each component. In this study, the variables are concentrations of selected major and trace elements and selected additional data on organic carbon and particle size. The combinations of elements and other properties that dominate the total variance may result from factors (such as chemical, geological, or biological) that determine the abundance of certain combinations of elements.

Because concentrations of some elements varied over several orders of magnitude, the principal component analysis was based on a correlation matrix of standardized variables that were log transformed (Davis, 1973). Principal component analysis requires available data for every variable for each site. A few values for mercury (sites 1, 5, and 27), selenium (sites 1 and 5), and sulfur (sites 1, 5, 8, and 27) were missing. To avoid eliminating these sites from the analysis, concentrations were estimated using the median of the appropriate site group. This procedure did not distort the analysis for sites without missing data.

The principal component analysis examines relations among concentrations of selected elements in the <62- μ m particle-size fraction of bed sediments collected from 22 sites in the different parts of the river system represented by the site groups (table 12). Trace elements included in the analysis were arsenic, chromium, copper, lead, lithium, mercury, nickel, selenium, and zinc. All of these elements, except for lithium, can have toxic effects on aquatic life when present in high concentrations (U.S. Environmental Protection Agency, 1986). Little is known about the effects of lithium on aquatic plants and animals. Iron and manganese were included because iron and manganese oxides form coatings on particles which are sites for trace-metal sorption. Aluminum and titanium were included because they are regarded as conservative elements, with a uniform contribution to bed sediments over a long

period of time from crustal rock sources (Horowitz, 1984). Organic carbon was included because of the tendency for trace elements to become concentrated in organic material (Horowitz, 1984). The clay-size fraction of bed sediments (<4 μm) was included because smaller particles have more surface area for adsorption of trace metals. Sulfur was added because of its association with selenium in westside ground water (Deverel and others, 1984) and soils (Tidball and others, 1986b). Data were not standardized to a conservative element (aluminum), to the clay fraction (percent <4 μm), or to total organic carbon, because correlations with elements in the <62- μm bed sediments were low and principal component analysis results were not improved.

The first four principal components account for a total of 78 percent of the variance in the data. The first and second components combined account for 57 percent of the variance, whereas the third and fourth account for only 21 percent. The remaining principal components each account for 6 percent or less of the total variance.

The first principal component accounts for 31 percent of the total variance (table 6). Positive variable loadings are greater than or equal to 0.20 for iron, chromium, lithium, nickel, zinc, aluminum, and copper, in order of dominance. Most of these elements occur mainly in the particulate phase in water (table 5). High negative loadings occur for mercury and titanium. The variance in scores computed for the first principal component from variable loadings and their values at each site relate partly to differences in element composition (table 6) among site groups (fig. 3).

With the exception of site 36, the clearest distinction among site groups based on the first-component scores is between westside tributaries, which are dominated by Coast Range sediments, and the eastside tributaries and lower San

Joaquin River, both of which are dominated by Sierra Nevada sediments. With the exception of zinc and iron, westside tributaries generally have higher concentrations of the dominant variables of the first component (fig. 2). This distinction may be related to two main factors: the greater abundance of these elements in Coast Range formations, and the greater dominance of fine-grained particles in Coast Range derived sediments. Aluminum, copper, iron, and zinc are often removed from solution by binding to fine particles (Johnson, 1986). Mercury and titanium concentrations generally were lowest in westside tributaries.

The second principal component is almost as dominant as the first component and accounts for 26 percent of the variance. The second component is dominated by high positive loadings for manganese, lead, copper, zinc, and total organic carbon in order of dominance, and high negative loadings for aluminum and <4- μm particle size (table 6). The second component indicates an association of the elements manganese, lead, copper, and zinc, primarily with organic matter in <62- μm sediments in which fine-grained and aluminum-rich particles of clay size are a relatively small proportion. Thus, component scores are highest for samples with high concentrations of trace elements and carbon and low concentrations of aluminum and <4- μm particles.

Together, the first and second components show a distinct separation between the site groups dominated by Sierra Nevada sediments--Mud and Salt Sloughs, the Eastside tributaries, and the lower San Joaquin River--and the westside tributaries that are dominated by Coast Range sediments (fig. 3). Results for site group 1, the upper San Joaquin River and tributaries, reasonably indicate a mixture of sediment sources (table 1).

The distribution of component scores by site group (fig. 3) shows the difference in bed-sediment composition of the eastside tributaries and Salt and Mud

TABLE 6.--Correlations of trace elements with the first four principal components

[Only variable loadings ≥ 0.20 are reported. Number in parentheses is percentage of total variance. <, less than; μm , micrometer]

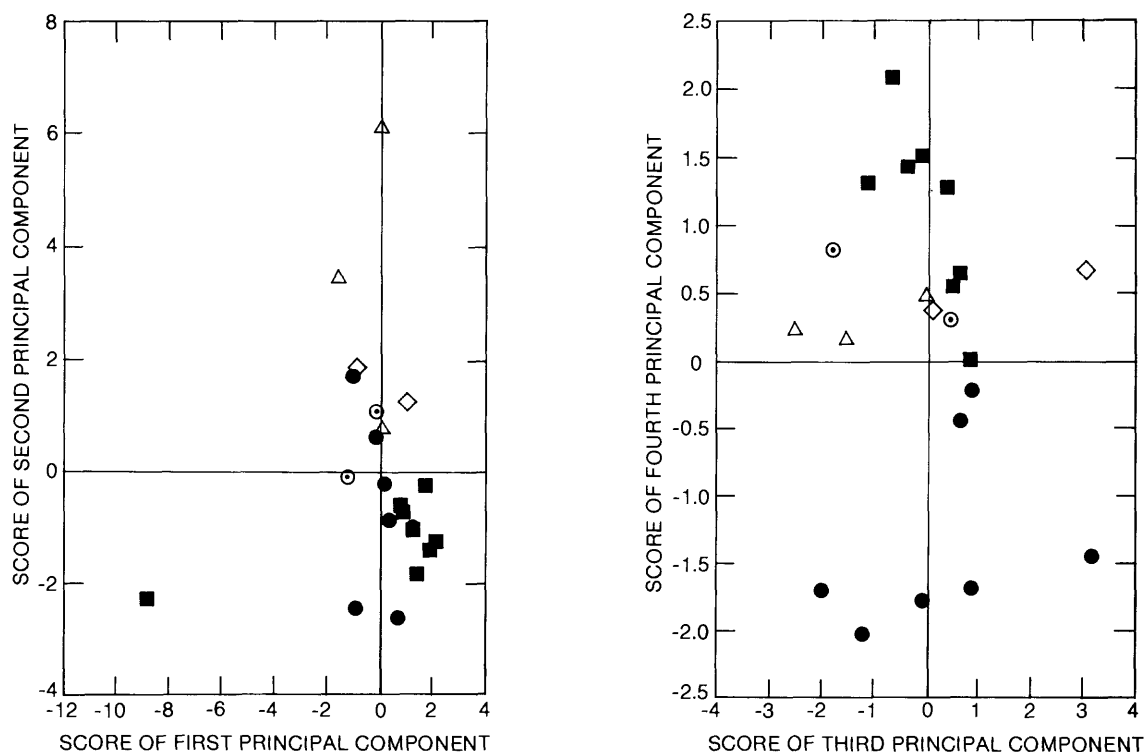
Variable loadings			
Principal component I (31)	Principal component II (26)	Principal component III (12)	Principal component IV (9)
Iron..... 0.41	Manganese.... 0.39	Sulfur..... 0.53	Titanium..... 0.49
Chromium... .38	Lead..... .38	Selenium..... .47	Nickel..... .44
Lithium.... .38	Copper..... .36	Arsenic..... .39	Arsenic..... .30
Nickel..... .34	Zinc..... .34	Carbon, .31	Chromium..... .30
Zinc..... .28	Carbon, .24	organic,	Selenium..... .20
Aluminum... .26	organic,	total.	Carbon, -.42
Copper..... .20	total.	Lead..... -.29	organic,
Mercury.... -.30	Aluminum..... -.34	Copper..... -.25	total.
Titanium... -.28	<4- μm -.33		Sulfur..... -.26
	particle		Zinc..... -.23
	size.		

Sloughs compared to the other site groups, which generally have low or negative scores. The eastside tributaries have the highest median concentrations of lead, and the sloughs have the highest median concentrations of manganese and zinc; both groups have lower median concentrations of aluminum compared to the other site groups (fig. 2). Samples from all sites in site groups 2 and 4 contain a very low percentage of fine-grained sediments, generally less than 9 percent <62 μm , and organic matter seems to be a more dominant factor affecting the trace-element composition at these sites.

The third principal component, which accounts for 12 percent of the variance, has positive loadings for sulfur, selenium, arsenic, and total organic carbon, and negative loadings for lead and copper, in order of dominance (table 6). The association of selenium and sulfur may result from the similar chemical behavior of selenium and sulfur and their common source. A variety of selenium minerals are found in certain sulfide deposits (Luttrell, 1959). Mudstones and

shales account for large sulfate concentrations in ground water near Los Banos, south of Kettleman City (Miller and others, 1971); and selenium and sulfur concentrations are correlated in shallow ground water in wells in the western San Joaquin Valley (Deverel and others, 1984). Arsenic has been used as a cotton defoliant in the western San Joaquin Valley. The association of arsenic, selenium, and sulfur with total organic carbon ($r^2=0.34$ to 0.61 ; $\alpha=0.05$ for log-transformed data) suggests that one way in which these elements are enriched in bed sediments in all parts of the river system is through biological uptake and sedimentation of organic detritus. The distribution of component scores by site groups (fig. 3) shows little distinction among site groups.

The fourth principal component accounts for only 9 percent of the variance, but shows some clear distinctions between site groups. High positive loadings occur for titanium, nickel, arsenic, chromium, and selenium, suggesting a Coast Range element assemblage, and high



EXPLANATION

SITE GROUP	NAME
● 1	Upper San Joaquin River
◇ 2	Salt and Mud Sloughs
■ 3	Westside tributaries
△ 4	Eastside tributaries
⊙ 5	Lower San Joaquin River

FIGURE 3. Principal component analysis of elements in < 62- μ m bed sediments.

negative loadings occur for total organic carbon, sulfur, and zinc. All site groups, except the upper San Joaquin River, have positive fourth component scores; the westside tributaries include the highest scores. The dominance of titanium, the negative loading for organic carbon, and the absence of iron and manganese as important variables in the fourth component may indicate that high positive scores identify sites where organic coatings or iron or manganese oxide coatings on particles are relatively unimportant factors in concentration of the dominant trace

elements. Conversely, negative scores for sites on the upper San Joaquin River may indicate that organic matter is a dominant factor in that intermittent reach of the river. As shown in figure 3, the combination of third and fourth component scores yields a distinct separation of sediment character between the upper San Joaquin River group and the other tributary groups. The sloughs, eastside tributaries, and lower San Joaquin River appear to show sediment characteristics midway between the upper San Joaquin River and the westside tributaries.

COMPARISON OF ELEMENTS IN BED SEDIMENTS AND VALLEY SOILS

San Joaquin Valley soils are a primary source of sediment and trace elements to the San Joaquin River basin through erosion of stream channels and agricultural lands. Total concentrations of elements in San Joaquin Valley soils collected from a depth of 0 to 30 cm were compared to whole streambed sediments from the San Joaquin River. Most elements in bed sediments were similar to reported values for valley soils (table 7). The coefficients of variation were calculated from the geometric mean and deviation for comparison to available geometric statistics on valley soils. The median coefficient of variation for 33 elements in valley soils was 0.13 $\mu\text{g/g}$, whereas for bed sediments, the coefficient of variation was 0.20 $\mu\text{g/g}$. The highest variation for major elements occurred for phosphorus and titanium; and highest variation for trace elements occurred for molybdenum, mercury, and selenium in soil and mercury and selenium in bed sediments. Total organic carbon also showed high variability. For phosphorus and total organic carbon, this is probably related to local variations in biological productivity or to fertilizer application; for mercury, to source areas and accumulation in organic matter; and for selenium, to local source areas of agricultural drain water and accumulation in organic matter through the biota.

Soil maps developed from trace-element data in San Joaquin Valley soils (R.R. Tidball, U.S. Geological Survey, written commun., 1986) show that arsenic, mercury, and selenium have generally similar areal distributions in soils near the river, with highest concentrations along the west side of the San Joaquin River and lowest concentrations on the east side of the river. Concentrations in soils near the San Joaquin River were 0.8 to 11 $\mu\text{g/g}$ for arsenic, 0.01 to

0.17 $\mu\text{g/g}$ for mercury, and 0.07 to 0.54 $\mu\text{g/g}$ for selenium, which compare to similar concentrations in San Joaquin River whole bed sediments of 1.3 to 8.0 $\mu\text{g/g}$ for arsenic, less than 0.02 to 0.12 $\mu\text{g/g}$ for mercury, and less than 0.1 to 0.3 $\mu\text{g/g}$ for selenium.

Copper and zinc concentrations showed similar areal distributions in valley soils, with source areas in both the Coast Range and the Sierra Nevada; a pattern apparent in the results of the principal component analysis. The lowest concentrations of copper and zinc in soil occurred near the San Joaquin River north of Fresno and west of Merced, and the highest concentrations occurred west of the San Joaquin River between Mendota and Newman. Near the San Joaquin River, soil concentrations ranged from 5 to 31 $\mu\text{g/g}$ for copper and 40 to 93 $\mu\text{g/g}$ for zinc. Concentration ranges were similar in whole bed sediments--2 to 62 $\mu\text{g/g}$ for copper and 15 to 110 $\mu\text{g/g}$ for zinc. Concentrations in bed sediments that were greater than maximum concentrations in soils occurred in Mariposa Slough (site 25) and Salt Slough (site 2) for copper, and in the same two sloughs and in the San Joaquin River near Turner Island (site 22) for zinc (table 14).

The areal distribution of lead in valley soils differed from the distribution of arsenic, mercury, selenium, copper, and zinc. Source areas for lead were near Fresno and Modesto, indicating probable urban sources, and lowest lead concentration occurred in soils in an area south of Merced. Neither the Sierra Nevada nor the Coast Range seem to be substantial lead sources. Concentrations in soils near the San Joaquin River ranged from 6.1 to 15 $\mu\text{g/g}$; and whole bed-sediment concentrations ranged from 13 to 29 $\mu\text{g/g}$, with highest concentrations in the San Joaquin River near Washington Bridge (site 21; 29 $\mu\text{g/g}$), below Mendota Pool (site 14; 21 $\mu\text{g/g}$) and in Salt Slough (site 2; 23 $\mu\text{g/g}$).

**TABLE 7.--Element concentrations in San Joaquin Valley soils
compared to bed sediments in the San Joaquin River basin**

[San Joaquin River whole bed-sediment statistics computed from 14 samples (table 14); San Joaquin Valley soils data summarized from R.R. Tidball, U.S. Geological Survey written commun., 1986; Cv, coefficient of variation is the geometric deviation divided by the geometric mean. $\mu\text{g/g}$, micrograms per gram]

Element	San Joaquin River basin whole bed sediments			San Joaquin Valley soils		
	Geometric			Geometric		
	Mean	Deviation	Cv	Mean	Deviation	Cv
<u>Major elements ($\mu\text{g/g}$)</u>						
Aluminum.....	70,800	11,100	0.16	75,200	11,100	0.15
Calcium.....	20,700	12,800	.62	24,800	14,400	.58
Iron.....	20,300	17,200	.85	31,800	13,800	.43
Magnesium.....	6,700	18,800	2.8	10,600	15,600	1.5
Phosphorus.....	4,190	16,800	4.0	630	16,200	26
Potassium.....	20,400	12,100	.59	17,100	13,800	.81
Sodium.....	20,000	11,600	.58	20,100	13,500	.67
Titanium.....	2,300	16,300	7.1	3,720	13,400	3.6
<u>Trace elements ($\mu\text{g/g}$)</u>						
Arsenic.....	4.26	1.76	0.41	4.57	1.90	0.42
Barium.....	837	1.16	.00	648	1.40	.00
Beryllium.....	.9	1.45	1.6	1.1	1.40	1.2
Cerium.....	35.0	1.35	.04	46.9	1.40	.03
Chromium.....	34.4	2.19	.06	54.2	1.81	.00
Cobalt.....	8.9	1.70	.19	11.9	1.42	.12
Copper.....	9.7	2.70	.28	18.9	1.80	.10
Gallium.....	14.2	1.21	.08	16.3	1.15	.07
Lanthanum.....	20.4	1.37	.07	26.1	1.40	.05
Lead.....	17.3	1.25	.07	15.2	1.47	.10
Lithium.....	18.6	1.92	.10	24.1	1.65	.07
Manganese.....	655	1.46	.00	628	1.36	.00
Mercury.....	.018	2.25	120	.022	2.36	110
Molybdenum.....	<2	--	--	.15	4.58	31
Neodymium.....	18.3	1.40	.08	23.7	1.31	.06
Nickel.....	21.1	2.48	.12	28.2	2.05	.07
Scandium.....	6.2	2.00	.32	10.7	1.46	.14
Selenium.....	.10	2.10	22	.14	2.54	18
Strontium.....	325	1.23	.00	321	1.34	.00
Thorium.....	8.1	1.80	.22	10.5	1.61	.15
Vanadium.....	52.2	1.80	.03	88.0	1.40	.02
Ytterbium.....	1.2	1.90	1.6	2.1	1.26	.61
Yttrium.....	11.6	1.40	.12	1.9	1.30	.07
Zinc.....	41.5	2.01	.05	67.4	1.38	.02
Carbon, organic, total.	1,700	48,600	29	8,300	19,400	2.3

ENVIRONMENTAL SIGNIFICANCE

Trace-element concentrations in bed sediments of the San Joaquin River basin are not unusually high compared to those from other rivers in either urban or agricultural basins. Median concentrations of trace elements in bed sediments in the San Joaquin River and its tributaries are much lower than those from some rivers in densely populated, industrial areas, such as the Ruhr and Rhine Rivers in Germany (table 8). Bed sediments in the San Joaquin River and its tributaries are comparable to sediments of the rural Willamette River in Oregon and the Ottawa and Rideau Rivers in Canada. Two exceptions are nickel concentrations, which are similar to Rhine

River concentrations but higher than in the Canadian rivers; and chromium concentrations, which are two to three times the concentration in the more rural rivers, but lower than in the industrialized rivers. Little is known about selenium concentrations in bed sediments of other rivers, and selenium may not even be detectable unless there is a contaminant source. Maximum trace-element concentrations in whole bed sediments from the San Joaquin River and tributaries are much less than total threshold limit concentrations allowed for hazardous solid wastes (California Department of Health Services, 1986; table 9), which would be a potential issue related to disposal of dredge spoils.

TABLE 8.--Comparison between trace-element concentrations in bed sediments from the San Joaquin River basin and other river systems

[San Joaquin River data are from median trace-element concentrations in <62- μ m bed sediments and are listed in table 12. Data for the Rhine and Ruhr Rivers are from trace elements in bed sediments described by Salomons and Forstner (1984, p. 172 and 177). Data for the Willamette River includes median trace-element concentrations from a total acid extraction of 44 samples of <20- μ m bed sediments (Rickert and others, 1977). Data for the Ottawa and Rideau Rivers includes mean background concentrations of trace elements from partial acid extraction of whole bed sediments (Oliver, 1973). <, less than; μ m, micrometer; μ g/g, micrograms per gram]

Element	Trace-element concentrations (μ g/g)					
	San Joaquin River (1985)	Rhine River (1970-80)	Ruhr River	Willamette River (1973)	Ottawa River	Rideau River
Arsenic.....	9.15	40-150	--	10	--	--
Cadmium.....	<2	30-50	25	1	--	--
Chromium.....	97.5	500-1,200	270	50	22	21
Copper.....	38	200-300	610	40	28	24
Cobalt.....	16	30-40	--	--	11	13
Lead.....	20	300-400	460	--	26	42
Mercury.....	.08	5-30	--	.14	.28	.20
Nickel.....	69	60-90	260	--	22	23
Zinc.....	110	1,500-2,000	3,040	185	84	86

TABLE 9.--Trace-element concentrations in bed sediments compared to hazardous waste criteria

[California Department of Health Services, 1986, p. 1800.77. <, less than; $\mu\text{g/g}$, micrograms per gram]

Element	Maximum concentration in 14 whole sediment samples ($\mu\text{g/g}$, wet wt.)	Hazardous waste total threshold limit ($\mu\text{g/g}$, wet wt.)
Arsenic.....	6.6	500
Barium.....	940	10,000
Beryllium.....	1.2	75
Cadmium.....	<2	100
Chromium.....	120	500
Cobalt.....	22	8,000
Copper.....	51	2,500
Lead.....	24	1,000
Mercury.....	.10	20
Molybdenum....	<2	3,500
Nickel.....	170	2,000
Selenium.....	.2	100
Silver.....	<2	500
Thorium.....	10	700
Vanadium.....	100	2,400
Zinc.....	91	5,000

SUMMARY

The purpose of this study was to assess the occurrence and distribution of trace elements in bed sediments of the San Joaquin River and its tributaries. The study was undertaken because of concerns that high concentrations of selenium or other trace elements from subsurface agricultural drain water or other sources may be concentrated in bed sediments.

Composite samples were collected of the upper 6 cm of bed sediment from representative cross sections at each of 24 sites. Concentrations of elements were higher and less variable in the <62- μm size fraction of bed sediments compared to whole samples. Bed sediments from eastside tributaries were much

coarser compared to westside tributaries. San Joaquin River sediments were a mixture from eastside and westside sources. The <62- μm size fraction was positively correlated with total organic carbon, although organic carbon generally occurred at low levels in the bed sediments sampled.

Only a few individual elements were distinctly different in concentration in different parts of the river system. Sediments of eastside tributaries, derived solely from Sierra Nevada sources, typically have low lithium and high manganese and zinc in the <62- μm size fraction. Selenium was highest in bed sediments of Salt and Mud Sloughs, where the highest selenium concentrations in water also have been measured.

Interrelations among trace elements, major elements, and other factors were examined using principal component analysis. Together, the first and second principal components account for 57 percent of the variance, and show a distinct separation between sites dominated by Coast Range and Sierra Nevada sediments. The dominance of the elements iron, chromium, lithium, zinc, aluminum, and copper in the first component may be related to their greater abundance in geologic formations in the Coast Range or to the greater dominance of fine-grained particles in the Coast Range compared to sediments derived from the Sierra Nevada. The second component indicates an association of the elements manganese, lead, copper, and zinc, primarily with organic matter in the <62- μm size fraction in sediments derived from the Sierra Nevada.

The third principal component explains 12 percent of the variance, and there is little distinction between site groups. However, the association of arsenic, selenium, and sulfur with total organic carbon indicates that one way these

elements are enriched in bed sediments in all site groups is through biological uptake and sedimentation of organic detritus. The fourth principal component explains 9 percent of the variance and shows positive scores for all sites except the upper San Joaquin River; the westside tributaries include the highest scores. The negative loading for organic carbon and the absence of iron and manganese in the fourth component may indicate sites where the concentration of the dominant trace elements--titanium, nickel, arsenic, chromium, and selenium--is not dependent on iron, manganese, or organic coatings. Organic matter, however, may be a dominant factor in the intermittent reach of the San Joaquin River.

Concentrations of elements in San Joaquin River bed sediments were similar to those of valley soils and were well below hazardous waste criteria which is a potential issue related to the disposal of dredge spoils from contaminated areas. Concentrations were lower than in sediments from polluted urban rivers and were more comparable to those of rivers in other rural agricultural areas. These results indicate that selenium and other trace elements are not at hazardous levels in the bed sediments of the San Joaquin River.

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TABLE 10.--Analyses of duplicate samples for major
and trace elements in bed sediments

[See table 1 for group and site names. Concentrations are on a dry weight basis.
<, less than; μm , micrometer; $\mu\text{g/g}$, micrograms per gram]

Element		Site group 1		Site group 3		Site
		Site 14	Site 25	Site 39	Site 42	group 4
		Whole	<62 μm	<62 μm	<62 μm	Site 8 Whole
<u>Major elements (μg/g)</u>						
Aluminum.....	1	80,000	78,000	83,000	83,000	59,000
	2	82,000	79,000	82,000	83,000	59,000
Calcium.....	1	21,000	30,000	13,000	12,000	19,000
	2	21,000	30,000	13,000	12,000	19,000
Iron.....	1	30,000	44,000	44,000	46,000	17,000
	2	30,000	44,000	43,000	46,000	17,000
Magnesium.....	1	9,800	18,000	15,000	17,000	5,300
	2	9,800	19,000	15,000	16,000	5,600
Phosphorus....	1	400	1,000	700	700	300
	2	400	1,000	700	700	300
Potassium.....	1	20,000	16,000	19,000	19,000	23,000
	2	21,000	16,000	19,000	18,000	23,000
Sodium.....	1	21,000	14,000	14,000	15,000	17,000
	2	21,000	14,000	14,000	15,000	17,000
Sulfur.....	1	<100	1,300	300	200	<100
	2	<100	1,400	300	100	<100
Titanium.....	1	3,600	3,900	3,800	3,300	1,700
	2	3,500	3,900	3,700	3,300	1,700
<u>Trace elements (μg/g)</u>						
Arsenic.....	1	4.5	8.3	12	9.6	2.7
	2	4.6	6.7	10	9.5	3.0
Barium.....	1	780	640	860	840	1,000
	2	790	650	850	830	1,000
Beryllium.....	1	1	1	1	1	<1
	2	1	1	1	1	<1
Cadmium.....	1	<2	<2	<2	<2	<2
	2	<2	<2	<2	<2	<2
Cerium.....	1	39	49	48	44	24
	2	43	51	49	43	26
Chromium.....	1	38	72	140	150	48
	2	38	73	130	160	52
Cobalt.....	1	11	16	19	19	7
	2	12	16	18	19	7
Copper.....	1	15	36	50	49	8
	2	15	38	51	48	6

TABLE 10.--Analyses of duplicate samples for major
and trace elements in bed sediments--Continued

Element		Site group 1		Site group 3		Site
		Site 14	Site 25	Site 39	Site 42	group 4
		Whole	<62 μm	<62 μm	<62 μm	Site 8 Whole
Trace elements (μg/g)--Continued						
Gallium.....	1	17	19	19	20	12
	2	18	19	18	19	12
Lanthanum.....	1	25	32	29	27	15
	2	27	32	29	27	16
Lead.....	1	21	18	21	16	14
	2	20	20	21	16	13
Lithium.....	1	37	55	61	53	9
	2	37	56	60	53	9
Manganese.....	1	610	820	870	620	490
	2	630	830	860	610	500
Mercury.....	1	.03	.05	.05	.08	<.02
	2	.03	.07	.06	.09	<.02
Molybdenum....	1	<2	<2	<2	<2	<2
	2	<2	<2	<2	<2	<2
Neodymium.....	1	23	28	26	25	13
	2	24	26	26	26	14
Nickel.....	1	23	52	94	94	24
	2	23	53	92	93	26
Scandium.....	1	10	12	15	16	5
	2	10	12	15	15	5
Selenium.....	1	<.1	.3	.5	.5	<.1
	2	<.1	.3	.5	.4	<.1
Strontium.....	1	290	320	200	230	350
	2	300	320	200	220	350
Thorium.....	1	10	18	12	11	<4
	2	13	18	12	11	6
Tin.....	1	<20	<20	<20	<20	<20
	2	<20	<20	<20	<20	<20
Vanadium.....	1	72	130	130	130	52
	2	72	130	120	130	52
Ytterbium.....	1	2	2	2	2	<1
	2	2	2	2	2	1
Yttrium.....	1	15	14	19	20	8
	2	15	14	19	19	8
Zinc.....	1	74	110	110	100	27
	2	74	120	110	100	26

TABLE 11.--Analyses of duplicate samples for carbon in bed sediments

[Site names are identified in table 1. Concentrations are on a dry weight basis in micrograms per gram. μm , micrometer]

Site No.	Sample type	Carbon, organic, total		Carbon, inorganic, total	
		1	2	1	2
1	whole	300	300	<100	<100
2	whole	2,000	2,000	1,200	1,200
5	whole	600	600	<100	<100
39	<62 μm	9,000	7,700	500	500
42	<62 μm	8,600	8,400	100	100

TABLE 12.--Trace elements, major elements, organic carbon,
particle size, and moisture content of <62- μ m bed sediments

[See table 1 for group and site names. --, indicates insufficient sample to run analysis.
Concentrations are on a dry weight basis. <, less than; μ m, micrometer; μ g/g, micrograms per gram]

Constituent	Site group 1						
	12	14	16	18	21	22	25
<u>Physical characteristics (percent)</u>							
Moisture.....	60	54	70	63	81	40	63
<62 μ m.....	85	39	2	2	67	93	94
<u>Major elements (μg/g)</u>							
Aluminum.....	83,000	89,000	80,000	79,000	74,000	82,000	78,000
Calcium.....	15,000	17,000	15,000	30,000	32,000	19,000	30,000
Iron.....	43,000	41,000	41,000	44,000	41,000	35,000	44,000
Magnesium.....	15,000	14,000	14,000	19,000	14,000	11,000	18,000
Phosphorus.....	700	600	1,000	1,000	1,100	800	1,000
Potassium.....	19,000	17,000	17,000	16,000	16,000	18,000	16,000
Sodium.....	14,000	16,000	14,000	14,000	14,000	19,000	14,000
Sulfur.....	300	100	400	1,400	4,200	300	1,300
Titanium.....	4,200	4,800	4,200	3,900	4,000	4,000	3,900
<u>Trace elements (μg/g)</u>							
Arsenic.....	12	5.9	10	6.7	16	5.4	8.3
Barium.....	710	710	720	650	770	720	640
Beryllium.....	1	2	1	1	1	1	1
Cadmium.....	<2	<2	<2	<2	<2	<2	<2
Cerium.....	54	52	48	51	46	53	49
Chromium.....	100	72	110	73	78	56	72
Cobalt.....	16	14	16	16	14	12	16
Copper.....	35	32	38	38	31	24	36
Gallium.....	19	19	18	19	18	18	19
Lanthanum.....	35	37	31	32	30	34	32
Lead.....	19	23	20	20	26	20	18
Lithium.....	56	59	48	56	50	45	55
Manganese.....	770	660	1,300	830	2,600	700	820
Mercury.....	.06	.20	.16	.07	.09	.07	.05
Molybdenum.....	<2	<2	<2	<2	<2	<2	<2
Neodymium.....	29	30	25	26	24	28	28
Nickel.....	69	43	69	53	43	35	52
Scandium.....	13	14	14	12	11	11	12
Selenium.....	.5	.2	.6	.3	.8	.2	.3
Strontium.....	250	250	240	320	300	290	320
Thorium.....	19	17	12	18	15	17	18
Tin.....	<20	<20	<20	<20	<20	<20	<20
Vanadium.....	110	100	110	130	100	87	130
Ytterbium.....	2	2	2	2	2	2	2
Yttrium.....	17	18	17	14	15	16	14
Zinc.....	110	110	110	120	130	93	110
Carbon, organic, total.	9,600	4,800	14,000	11,000	29,000	10,000	17,000
Carbon, inorganic, total.	<100	<100	100	200	4,200	500	4,900

TABLE 12.--Trace elements, major elements, organic carbon, particle size, and moisture content of <62- μ m bed sediments--Continued

Constituent	Site group 2		Site group 3				
	2	4	29	32	34	35	36
<u>Physical characteristics (percent)</u>							
Moisture.....	94	77	60	64	38	55	45
<62 μ m.....	9	8	50	41	41	15	16
<u>Major elements (μg/g)</u>							
Aluminum.....	75,000	79,000	82,000	80,000	78,000	82,000	70,000
Calcium.....	19,000	23,000	17,000	32,000	11,000	10,000	25,000
Iron.....	41,000	50,000	42,000	44,000	40,000	39,000	18,000
Magnesium.....	12,000	21,000	17,000	25,000	15,000	12,000	5,400
Phosphorus.....	1,000	700	600	900	700	600	500
Potassium.....	17,000	19,000	22,000	23,000	17,000	20,000	21,000
Sodium.....	17,000	14,000	19,000	15,000	15,000	13,000	23,000
Sulfur.....	500	6,600	100	200	500	300	300
Titanium.....	3,600	3,800	4,000	3,500	3,600	3,900	2,300
<u>Trace elements (μg/g)</u>							
Arsenic.....	11	9.3	7.4	12	7.6	13	8.2
Barium.....	690	690	770	780	660	770	920
Beryllium.....	1	1	2	1	1	1	1
Cadmium.....	12	<2	<2	<2	<2	<2	<2
Cerium.....	49	44	52	41	44	49	44
Chromium.....	84	180	110	150	140	95	22
Cobalt.....	13	20	16	19	17	15	11
Copper.....	66	40	33	37	46	40	8
Gallium.....	17	20	20	18	18	18	13
Lanthanum.....	28	28	34	26	27	30	23
Lead.....	240	20	19	17	15	21	21
Lithium.....	43	57	51	58	51	63	16
Manganese.....	1,600	1,300	870	960	630	740	1,500
Mercury.....	.08	.17	.06	.05	.06	.05	.40
Molybdenum.....	<2	3	<2	<2	<2	<2	<2
Neodymium.....	22	23	26	21	24	27	21
Nickel.....	55	120	90	120	100	61	22
Scandium.....	12	15	12	13	13	13	5
Selenium.....	.9	1.5	.5	.2	.5	.6	.6
Strontium.....	290	290	310	440	190	210	350
Thorium.....	13	14	17	11	11	13	8
Tin.....	<20	<20	<20	<20	<20	<20	<20
Vanadium.....	94	120	98	120	110	110	44
Ytterbium.....	2	2	2	2	2	2	2
Yttrium.....	15	17	17	15	17	18	14
Zinc.....	100	110	100	93	99	110	34
Carbon, organic, total.	9,500	8,600	2,100	2,600	9,600	9,100	9,900
Carbon, inorganic, total.	700	3,600	100	8,000	100	100	200

TABLE 12.--Trace elements, major elements, organic carbon, particle size, and moisture content of <62- μ m bed sediments--Continued

Constituent	Site group 3--Continued			Site group 4			Site group 5	
	39	40	42	5	8	27	1	3
<u>Physical characteristics (percent)</u>								
Moisture.....	53	53	55	96	86	77	84	70
<62 μ m.....	14	56	72	<1	<1	<1	1	4
<u>Major elements (μg/g)</u>								
Aluminum.....	83,000	87,000	83,000	66,000	72,000	79,000	80,000	79,000
Calcium.....	13,000	11,000	12,000	18,000	19,000	29,000	19,000	20,000
Iron.....	44,000	49,000	46,000	45,000	41,000	45,000	41,000	41,000
Magnesium.....	15,000	18,000	17,000	11,000	12,000	15,000	13,000	12,000
Phosphorus.....	700	600	700	1,000	1,300	1,000	800	1,000
Potassium.....	19,000	21,000	19,000	14,000	12,000	19,000	18,000	18,000
Sodium.....	14,000	13,000	15,000	13,000	14,000	17,000	17,000	18,000
Sulfur.....	300	200	200	--	--	--	--	300
Titanium.....	3,800	3,400	3,300	3,700	3,900	3,900	3,700	4,000
<u>Trace elements (μg/g)</u>								
Arsenic.....	12	10	9.6	<20	13	8.9	<10	12
Barium.....	860	920	840	990	970	950	740	740
Beryllium.....	1	1	1	1	1	1	1	1
Cadmium.....	<2	<2	<2	15	<2	<2	2	<2
Cerium.....	48	43	44	42	48	73	52	52
Chromium.....	140	160	150	130	110	85	95	82
Cobalt.....	19	19	19	21	19	30	15	13
Copper.....	50	56	49	560	52	35	100	23
Gallium.....	19	19	20	16	19	19	17	19
Lanthanum.....	29	27	27	23	29	38	29	33
Lead.....	21	18	16	790	56	26	92	17
Lithium.....	61	62	53	29	25	41	39	43
Manganese.....	870	910	620	4,400	4,200	3,400	930	1,400
Mercury.....	.05	.09	.08	--	.25	--	--	.18
Molybdenum.....	<2	<2	<2	2	<2	<2	<2	<2
Neodymium.....	26	24	25	19	25	28	24	26
Nickel.....	94	100	94	79	83	71	60	43
Scandium.....	15	17	16	15	14	12	14	11
Selenium.....	.5	.3	.5	--	.6	<.2	--	.5
Strontium.....	200	190	230	230	270	340	290	300
Thorium.....	12	10	11	10	13	19	12	16
Tin.....	<20	<20	90	<20	<20	<20	<20	<20
Vanadium.....	130	140	130	130	130	110	100	97
Ytterbium.....	2	2	2	<2	2	3	2	2
Yttrium.....	19	20	20	15	18	22	16	18
Zinc.....	110	110	100	230	150	130	130	91
Carbon, organic, total.	9,000	4,400	8,600	13,000	19,000	5,600	11,000	9,900
Carbon, inorganic, total.	500	100	100	300	400	3,000	200	300

TABLE 13.--Trace elements, major elements, organic carbon, particle size, and moisture content of >62- μ m bed sediments

[See table 1 for group and site names. Concentrations are on a dry weight basis.
<, less than; μ m, micrometer; μ g/g, micrograms per gram]

Constituent	Site group 1			Site group 2	Site group 3	Site group 4
	14	22	25	2	36	5
<u>Physical characteristics (percent)</u>						
Moisture.....	19	57	41	18	18	21
<62 μ m.....	39	93	94	9	16	<1
<u>Major elements (μg/g)</u>						
Aluminum.....	74,000	80,000	76,000	65,000	83,000	81,000
Calcium.....	24,000	19,000	24,000	18,000	18,000	21,000
Iron.....	23,000	32,000	22,000	15,000	45,000	36,000
Magnesium.....	7,600	11,000	8,000	5,000	14,000	12,000
Phosphorus.....	300	600	900	300	1,200	1,000
Potassium.....	22,000	21,000	20,000	23,000	15,000	19,000
Sodium.....	23,000	22,000	24,000	20,000	17,000	21,000
Sulfur.....	<100	300	900	<100	100	<100
Titanium.....	2,800	3,200	2,500	1,500	4,000	3,600
<u>Trace elements (μg/g)</u>						
Arsenic.....	3.1	8.7	4.6	5.7	5.4	3.9
Barium.....	770	760	750	960	710	730
Beryllium.....	1	1	1	<1	1	1
Cadmium.....	<2	<2	<2	<2	<2	<2
Cerium.....	36	39	36	24	49	47
Chromium.....	23	41	32	31	80	62
Cobalt.....	9	16	10	6	15	13
Copper.....	4	27	18	9	44	21
Gallium.....	17	18	16	14	20	18
Lanthanum.....	21	25	22	15	33	29
Lead.....	17	20	19	17	28	20
Lithium.....	21	42	23	12	51	40
Manganese.....	530	670	470	790	2,100	1,100
Mercury.....	.02	.04	.04	.02	.05	<.02
Molybdenum.....	<2	<2	<2	<2	<2	<2
Neodymium.....	21	20	20	15	27	27
Nickel.....	12	34	25	14	56	39
Scandium.....	8	8	6	5	12	10
Selenium.....	<.1	.2	.2	<.1	.2	<.1
Strontium.....	320	310	360	320	280	320
Thorium.....	9	10	7	4	17	13
Tin.....	<20	<20	<20	<20	<20	<20
Vanadium.....	55	78	71	47	100	83
Ytterbium.....	2	2	1	<1	2	2
Yttrium.....	13	12	12	7	16	15
Zinc.....	48	94	58	29	110	85
Carbon, organic, total.	7,800	28,000	18,000	1,500	4,600	700
Carbon, inorganic, total.	300	300	1,100	700	700	<100

TABLE 14.--Trace elements, major elements, organic carbon, particle size, and moisture content of whole bed sediments

[See table 1 for group and site names. Concentrations are on a dry weight basis.
<, less than; μm , micrometers; $\mu\text{g/g}$, micrograms per gram]

Constituent	Site group 1					Site group 2	
	14	18	21	22	25	2	4
<u>Physical characteristics (percent)</u>							
Moisture.....	19	--	--	42	59	17	--
<62 μm	39	2	67	93	94	9	8
<u>Major elements ($\mu\text{g/g}$)</u>							
Aluminum.....	80,000	63,000	78,000	82,000	79,000	81,000	69,000
Calcium.....	21,000	18,000	29,000	19,000	29,000	11,000	24,000
Iron.....	30,000	11,000	25,000	35,000	41,000	44,000	11,000
Magnesium.....	9,800	3,300	9,000	11,000	17,000	19,000	4,500
Phosphorus.....	400	200	500	700	1,000	700	300
Potassium.....	20,000	23,000	18,000	13,000	17,000	17,000	25,000
Sodium.....	21,000	19,000	24,000	19,000	16,000	15,000	23,000
Sulfur.....	<100	<100	1,100	200	1,200	100	600
Titanium.....	3,600	1,100	2,700	3,900	3,800	3,800	1,400
<u>Trace elements ($\mu\text{g/g}$)</u>							
Arsenic.....	4.5	6.2	8.0	7.1	8.0	8.0	2.7
Barium.....	780	860	680	690	750	680	930
Beryllium.....	1	1	1	2	1	1	1
Cadmium.....	<2	<2	<2	<2	<2	<2	<2
Cerium.....	39	22	34	51	52	44	34
Chromium.....	38	7	39	53	68	150	21
Cobalt.....	11	5	10	13	15	26	6
Copper.....	15	4	9	26	34	62	6
Gallium.....	17	11	16	19	19	17	12
Lanthanum.....	25	12	18	33	33	26	17
Lead.....	21	17	29	18	19	23	15
Lithium.....	37	14	24	45	52	50	12
Manganese.....	610	500	920	720	810	690	740
Mercury.....	.03	<.02	.03	.04	.05	<.02	.02
Molybdenum.....	<2	<2	<2	<2	<2	<2	<2
Neodymium.....	23	11	17	28	26	25	15
Nickel.....	23	5	17	36	48	200	17
Scandium.....	10	4	10	10	11	16	4
Selenium.....	<.1	<.1	.3	.2	.3	.1	.2
Strontium.....	290	310	360	290	330	180	380
Thorium.....	10	5	8	17	16	12	10
Tin.....	<20	<10	<10	<20	<20	<20	<10
Vanadium.....	72	23	56	87	120	120	25
Ytterbium.....	2	<1	2	2	2	2	1
Yttrium.....	15	7	14	16	15	18	11
Zinc.....	74	22	61	94	110	110	20
Carbon, organic, total.	7,800	--	--	12,000	17,000	2,000	--
Carbon, inorganic, total.	300	--	--	500	4,700	1,200	--

TABLE 14.--Trace elements, major elements, organic carbon, particle size,
and moisture content of whole bed sediments--Continued

Constituent	Site group 3	Site group 4				Site group 5	
	36	5	8	10	27	1	11
<u>Physical characteristics (percent)</u>							
Moisture.....	13	21	15	22	4	12	--
<62 μ m.....	16	<1	1	<1	<1	<1	<1
<u>Major elements (μg/g)</u>							
Aluminum.....	72,000	71,000	59,000	69,000	63,000	66,000	64,000
Calcium.....	22,000	27,000	19,000	22,000	19,000	20,000	18,000
Iron.....	29,000	19,000	17,000	23,000	6,800	16,000	15,000
Magnesium.....	9,200	6,000	5,300	7,600	2,100	3,300	4,700
Phosphorus.....	600	600	300	500	200	200	400
Potassium.....	18,000	21,000	23,000	23,000	26,000	24,000	23,000
Sodium.....	19,000	24,000	17,000	21,000	21,000	23,000	20,000
Sulfur.....	<100	<100	<100	<100	<100	<100	<100
Titanium.....	3,000	2,800	1,700	2,700	900	2,60	1,500
<u>Trace elements (μg/g)</u>							
Arsenic.....	5.8	5.6	2.7	2.5	3.0	1.3	2.8
Barium.....	800	870	1,000	1,000	980	810	1,000
Beryllium.....	1	1	<1	1	1	1	<1
Cadmium.....	<2	<2	<2	<2	<2	<2	<2
Cerium.....	34	47	24	28	24	49	28
Chromium.....	52	24	48	51	11	18	45
Cobalt.....	12	10	7	12	4	4	7
Copper.....	23	7	8	9	3	2	5
Gallium.....	15	15	12	14	11	13	12
Lanthanum.....	22	25	15	17	14	26	16
Lead.....	17	18	14	14	16	14	13
Lithium.....	18	16	9	13	9	10	11
Manganese.....	910	1,400	490	630	350	340	690
Mercury.....	.12	<.02	<.02	<.02	<.02	<.02	<.02
Molybdenum.....	<2	<2	<2	<2	<2	<2	<2
Neodymium.....	21	26	13	15	12	25	13
Nickel.....	27	18	24	29	9	6	17
Scandium.....	11	6	5	6	1	4	5
Selenium.....	.2	<.1	<.1	<.1	<.1	<.1	<.1
Strontium.....	300	350	350	440	350	340	370
Thorium.....	9	10	4	12	5	8	5
Tin.....	<20	<20	<20	<20	<20	<20	<10
Vanadium.....	83	48	52	66	18	39	40
Ytterbium.....	1	2	<1	1	<1	2	<1
Yttrium.....	12	15	8	9	7	15	8
Zinc.....	67	40	27	40	15	21	22
Carbon, organic, total.	4,000	600	800	200	200	300	--
Carbon inorganic, total.	3,800	<100	<100	800	<100	<100	--