STREAMFLOW, DISSOLVED SOLIDS, SUSPENDED SEDIMENT, AND TRACE ELEMENTS, SAN JOAQUIN RIVER, CALIFORNIA, JUNE 1985-SEPTEMBER 1988

By Barry R. Hill *and* Robert J. Gilliom

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-4085

Prepared in cooperation with the

SAN JOAQUIN VALLEY DRAINAGE PROGRAM

6439-88

Sacramento, California
1993

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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Conversion Factors

Multiply	By	To obtain
cubic meter (m^3)	35.31	cubic foot
cubic meter per second (m^3/s)	35.31	cubic foot per second
hectare (ha)	2.471	acre
kilogram per day (kg/d)	2.205	pound per day
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per kilometer (m/km)	0.1895	foot per mile
millimeter (mm)	0.03937	inch

Temperature is given in degree Celsius (°C), which can be converted to degree Fahrenheit (°F) by the following equation:

$$°F=1.8(°C)+32.$$

Water-Quality Information

Chemical concentrations are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams and micrograms per liter are units expressing the weight of the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. Micrograms per liter is equivalent to "parts per billion." Milligrams per liter is equivalent to "parts per million."

Vertical Datum

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Water quality in the San Joaquin River and its major tributaries was studied during 1985-88 in response to concern about adverse effects of agricultural wastewater on the river. The 1985-88 study period included hydrologic extremes throughout most of central California. Except for an 11-month period during and after the 1986 flood, streamflows in the San Joaquin River during the study period generally were less than median streamflows for 1975-88. Combined streamflow from the Sierra Nevada tributaries (Merced, Tuolumne, and Stanislaus Rivers) comprised 56 to 69 percent of the annual streamflow of the San Joaquin River, combined streamflow from Salt and Mud Sloughs comprised 6 to 19 percent, the upper San Joaquin River comprised 2 to 25 percent, and unmeasured sources of water from agricultural discharges and ground water accounted for 13 to 20 percent. Salt and Mud Sloughs and the unmeasured sources of water contribute most of the dissolved-solids load in the San Joaquin River. The Merced, Tuolumne, and Stanislaus Rivers greatly affect dissolved-solids concentrations through dilution. Suspended-sediment concentration peaked sharply at more than 600 milligrams per liter during the flood of February 1986. Concentrations and loads of suspended sediment varied seasonally during low-flow conditions; concentrations were highest during the early summer irrigation season.

Trace elements present primarily in dissolved phases are arsenic, boron, lithium, molybdenum, and selenium. Boron concentrations exceeded the irrigation water-quality criterion of 750 micrograms per liter more than 75 percent of the time in Salt and Mud Sloughs and more than 50 percent of the time at three sites on the San Joaquin River. Selenium concentrations exceeded the aquatic-life water-quality criterion of 5 micrograms per liter more than 75 percent of the time in Salt Slough and more than 50 percent of the time in Mud Slough and in the San Joaquin River from Salt Slough to the Merced River confluence. Concentrations of dissolved solids, boron, and selenium usually were highest during late winter to early spring, followed by lower concentrations in early summer, higher concentrations again in mid-to-late summer, and the lowest concentrations of the year in the autumn. These concentrations generally correspond to the seasonal patterns in the inflow of subsurface tile drainwater to Salt and Mud Sloughs. Trace elements present primarily in particulate phases are aluminum, chromium, copper, iron, manganese, nickel, and zinc, none of which cause significant water-quality problems in the river.

INTRODUCTION

Agricultural drainage problems in the San Joaquin Valley, California, have attracted national attention since 1983, when selenium in water from subsurface tile-drainage systems was found to have toxic effects on fish and waterfowl at Kesterson Reservoir (Presser and Barnes, 1984; Hamilton and others, 1986; Ohlendorf and others, 1986a, 1986b). Similar drainwater from about 31,000 ha (hectare) of agricultural land is discharged to the San Joaquin River or its tributaries (California State Water Resources Control Board, 1987). Concern about adverse effects of this drainwater and other agricultural wastewater on the quality of the San Joaquin River prompted a study of the water quality of the San Joaquin River from 1985 to 1988. This study is part of a comprehensive investigation of the hydrology and geochemistry of the San Joaquin Valley by the U.S. Geological Survey in cooperation with the San Joaquin Valley Drainage Program.

This report provides an overview of selected hydrologic and water-quality conditions in the San Joaquin River and its major tributaries during June 1985 to September 1988. This overview serves as a descriptive introduction for more detailed analyses of the sources and transport of contaminants, such as reported by Clifton and Gilliom (1989). Data discussed in this report include results of biweekly or monthly water-quality sampling at 11 sites between June 1985 and September 1988, and continuous records of streamflow and specific conductance collected at the same sites from October 1985 to September 1988.

Specific objectives of this report are to summarize:

(1) Hydrologic conditions during the study period and how they compare with historical conditions;
(2) Concentrations and sources of dissolved solids in the river and the relations between tributary sources of dissolved solids and ion composition;
(3) Suspended-sediment concentrations and sources; and
(4) Trace-element concentrations and the partitioning between dissolved and particulate phases.

STUDY AREA

The San Joaquin Valley (fig. 1) is a major structural depression lying between the Coast Ranges to the west and the Sierra Nevada to the east. It is bounded by the Tehachapi Mountains to the south and the combined delta of the Sacramento and San Joaquin Rivers to the north. The Coast Ranges are composed primarily of rocks of the Franciscan complex and overlying marine and continental sedimentary rocks of Tertiary age (Lettis, 1982). The Sierra Nevada and the Tehachapi Mountains are composed largely of pre-Tertiary granitic rocks. The valley floor is underlain by more than 1,000 m of unconsolidated sediments that originated from erosion of the mountains flanking the valley (Belitz and Heimes, 1989). The floor of the valley has little topographic relief and the gradient of the San Joaquin River is correspondingly low (about 0.15 m/km through the study reach).

The climate of the San Joaquin Valley is arid to semiarid. Average annual rainfall generally ranges from 150 to 300 mm (Rantz, 1969). Almost all precipitation falls as rain during mild winters. Summers are hot and dry. Long-term precipitation records (30 years) are available for Los Banos, located in the southern part of the study area (fig. 1). Average annual rainfall at Los Banos is 230 mm (National Weather Service, 1988). Annual rainfall during the study period ranged from about 60 percent of the long-term average in 1988 to about 120 percent in 1987 (fig. 2).

The major land use in the valley is agriculture, and an extensive network of storage reservoirs and canals, as well as numerous wells, provides the valley with irrigation water throughout most of the year. The history of water development, irrigation, and agricultural drainage in the San Joaquin Valley was described by the California State Water Resources Control Board (1987).

Below its headwaters in the Sierra Nevada, the San Joaquin River flows 309 km from Friant Dam in the foothills to Vernalis (fig. 1), which is just upstream from tidal backwater influence of the Sacramento-San Joaquin Delta. River gradients range from 0.6 m/km near Friant Dam to 0.1 m/km near Vernalis. Within the first 105 km between Friant Dam and Mendota Pool, the river generally has intermittent streamflow, and usually river water from the headwaters does not reach Mendota Pool near Mendota because of diversions below Friant Dam. In the next 108 km between Mendota Pool and site 1 near Stevinson, the river also has intermittent streamflow, except for a reach of several kilometers just downstream of Mendota Pool, in which flow is perennial. Streamflow in the remaining 96 km, between site 1 near Stevinson and site 11 near Vernalis, is perennial and increases downstream as tributaries and irrigation-return flows enter the river. Inflows to this part of the river come from surface runoff and subsurface drainwater from irrigated areas, ground water, and runoff from the Sierra Nevada.

This study focuses on data from 11 sites on the perennial flow part of the San Joaquin River and its tributaries (fig. 1). Water that reaches the perennial flow part of the San Joaquin River from the predominantly intermittent parts of the river upstream from Stevinson is monitored in the San Joaquin River near Stevinson (site 1). During low-flow conditions, most water reaching site 1 is irrigation-return flow,

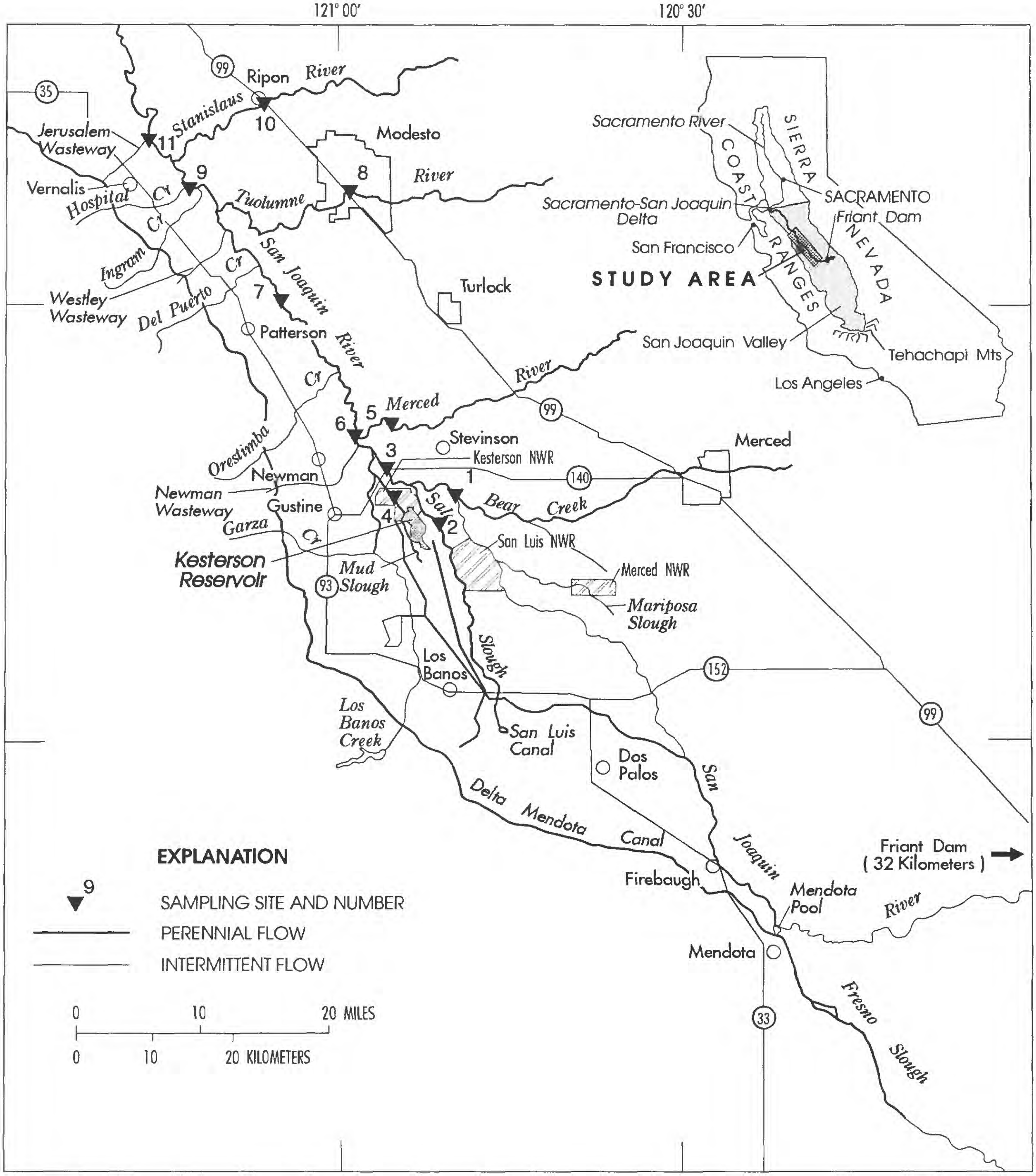

Figure 1. Location of sites sampled.

but during high-flow periods, most of the water is runoff from the Sierra Nevada.

The first tributaries to enter the river downstream from the Stevinson site are Salt Slough (site 2) and Mud Slough (site 4), with a combined drainage area of 123,000 ha. One source of water in these sloughs is subsurface agricultural drainwater, some of which is high in dissolved solids and dissolved selenium. The sloughs also receive irrigation-return flows and ground-water inflow. The sloughs are connected upstream to a network of water distribution and drain-

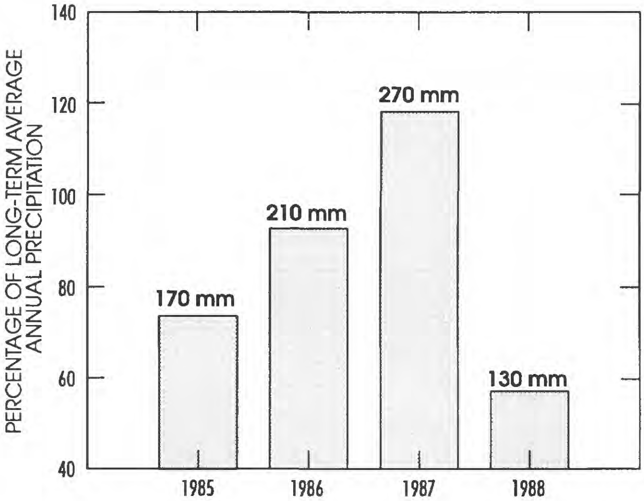

Figure 2. Annual precipitation at Los Banos during 1985-88 as a percentage of long-term average annual precipitation. Number is precipitation, in millimeters, for indicated year. (Data from National Weather Service, 1986a, 1986b, 1988, 1989).

water collection canals so that some inflows can be alternately conveyed to one slough or the other.

Three major tributaries, which originate in the Sierra Nevada, account for most of the tributary inflow to the San Joaquin River (Hunter and others, 1987). From south to north, these tributaries are the Merced River (site 5), the Tuolumne River (site 8), and the Stanislaus River (site 10). Their combined drainage area is about 1 million ha. Twenty percent of the natural flow in these tributaries during high runoff years and as much as 90 percent of the flow during low runoff years is stored in reservoirs or diverted for irrigation. The lower reaches of these tributaries receive substantial quantities of irrigation-return flows.

METHODS

Instantaneous streamflow during water-quality sample collection was determined from stage-discharge relations as described by Rantz (1982). Water-quality samples were collected using the equal-width increment method (U.S. Geological Survey, 1977), which provides for isokinetic depth-integrated samples that are representative of conditions throughout the channel cross section. Field measurements of specific conductance, pH, water temperature, and dissolved oxygen were made with portable instruments. Total, carbonate, and bicarbonate alkalinity were determined in the field by incremental titration (Barnes, 1964). Samples were processed and preserved in the field following procedures described by Ward and Harr (1990).

Water samples were analyzed at the U.S. Geological Survey's National Water Quality Laboratory in Arvada, Colorado, following procedures described by Skougstad and others (1979). Additional selenium analyses were performed at the U.S. Geological Survey laboratory in Sacramento, California. Calcium, magnesium, sodium, potassium, aluminum, chromium, copper, iron, lithium, manganese, molybdenum, nickel, selenium, and zinc concentrations were determined by atomic absorption spectrophotometry. Sulfate, chloride, fluoride, arsenic, and boron concentrations were determined with colorimetric methods (Skougstad and others, 1979).

STREAMFLOW, DISSOLVED SOLIDS, AND SUSPENDED SEDIMENT

HISTORICAL HYDROLOGIC PERSPECTIVE

The 1985-88 study period included hydrologic extremes throughout most of central California. During 1986, flooding affected much of the San Joaquin Valley. Drought conditions for streamflow prevailed in the region during 1987 and 1988. Within the study area, however, rainfall did not vary greatly from year to year (fig. 2). Rainfall was actually higher during the drought year of 1987 than during the flood year of 1986.

Clifton and Gilliom (1989) partitioned their 1985-87 study period into two distinct periods based on flow variations at site 11: a low-flow period extending from October 1985 to mid-February 1986 and from mid-May 1986 to September 1987, and a high-flow period extending from mid-February to mid-May 1986. This classification is retained in this study, with the low-flow period extended to September 1988. Daily mean streamflow at site 11 (fig. 1) for the 1985-88 study period is shown in figure 3. Also shown are monthly streamflows expressed as percentiles of the monthly mean totals for the 1975-88 period. Streamflow data are from Hunter and others (1987, 1988a, 1988b) and Mullen and others (1989). Except for an 11-month period during and after the 1986 flood, streamflows during the study period generally were less than the median for the 1975-88 period. Although flooding was

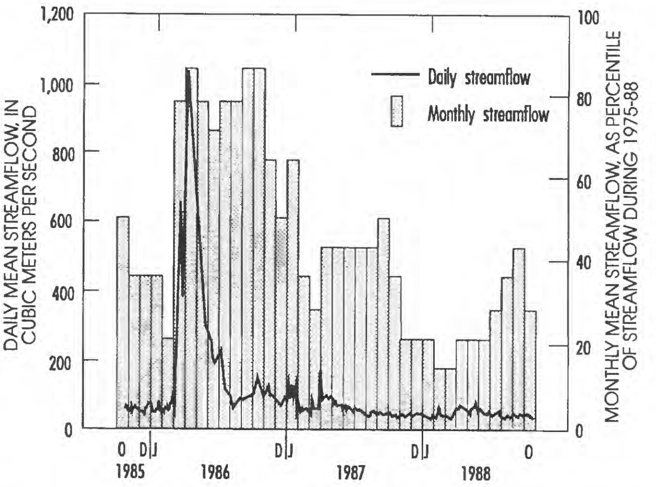

Figure 3. Streamflow of the San Joaquin River near Vernalis (site 11).

extensive during early 1986, the peak flow at site 11 during the 1986 flood was less than one-half the peak flow for the period of record, which occurred in 1950 (Hunter and others, 1988a).

SOURCES OF STREAMFLOW AND DISSOLVED SOLIDS

To facilitate analysis, water-quality data were classified by site or by groups of sites. Site 1, representing the upper San Joaquin River, was considered unique and was not grouped with other sites. Streamflow at site 1 is composed primarily of agricultural return flows during the low-flow period (Clifton and Gilliom, 1989), but consists largely of Sierra Nevada runoff during the high-flow period. Even though site 1 is on the San Joaquin River, it was considered a tributary site for purposes of this study. Sites 2 and 4 on Salt and Mud Sloughs were grouped together because streamflow at both sites is composed primarily of irrigation return flows, ground water, and subsurface agricultural drain water. Sites 5, 8, and 10 are on the Merced, Tuolumne, and Stanislaus Rivers, which originate in the Sierra Nevada, and were grouped together accordingly as the Sierra Nevada tributaries. Site 11 represents conditions in the San Joaquin River downstream from all tributary inflows. Water-quality data collected at sites 3, 6, 7, and 9 on the San Joaquin River reflect mixing of waters from different combinations of tributaries.

The total volume of water passing site 11 during the 1986 flood year was greater than the total volume of streamflow during the three low-flow years combined (table 1). Annual streamflow varied greatly at all sites except for those on Salt and Mud Sloughs. All sites except those on the sloughs are on streams that carried high runoff from the Sierra Nevada during the 1986 flood. Streamflow at Salt Slough (site 2) was nearly as high during 1987 and 1988 as during 1986. Streamflow at Mud Slough (site 4) was higher in 1986 than in 1987 and 1988, but only by a factor of two.

Table 1. Annual streamflow at sites 1-11, water years 1985-88

[The water year begins October 1 and ends September 30, and is designated in the year in which it ends; Asterisk (*) indicates tributary site; --, no data]

Site No. (fig. 1)	Annual streamflow (millions of cubic meters)				Annual streamflow as percentage of streamflow at site 11			
	1985	1986	1987	1988	1985	1986	1987	1988
*1	--	1,629	52	25	--	25	2	2
*2	--	244	237	237	--	4	11	16
3	--	2,030	306	259	--	31	14	18
*4	--	107	52	48	--	2	2	3
*5	369	769	196	136	14	12	9	9
6	713	2,943	601	490	27	46	27	34
7	--	3,302	--	--	--	51	--	--
*8	732	1,646	645	193	28	26	29	13
9	--	--	1,758	--	--	--	79	--
*10	700	1,193	656	537	27	18	29	37
11	2,601	6,450	2,238	1,441	100	100	100	100

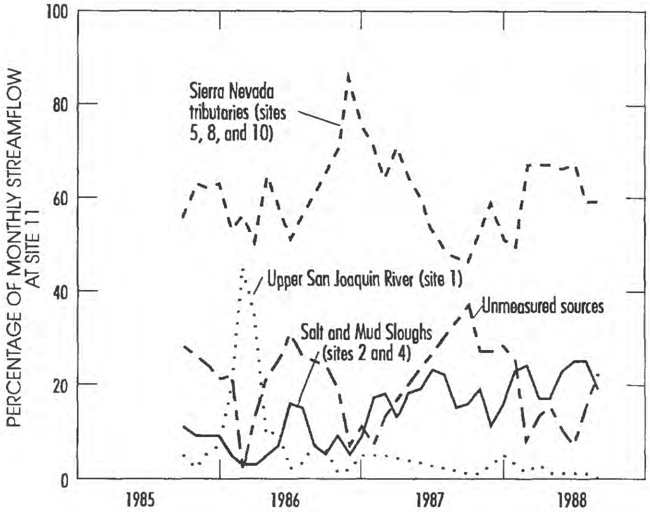

Figure 4. Relative contributions of streamflow to the San Joaquin River from major sources.

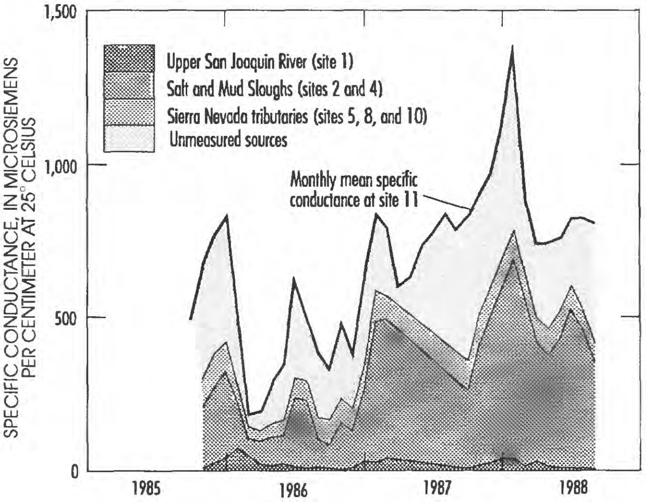

Figure 5. Monthly mean specific conductance of the San Joaquin River near Vernalis (site 11), and the estimated proportion of specific conductance attributed to dissolved-solids loading from tributary and unmeasured sources.

Relative contributions of streamflow from major sources (sites 1, 2, 4, 5, 8, and 10) to monthly streamflow at site 11 did not differ greatly between the 1986 flood year and the three low-flow years (table 1; fig. 4). Sites 1 and 2 were exceptions (table 1). Streamflow at site 1 comprised 25 percent of the streamflow at site 11 in 1986 because of flood conditions, but only 2 percent in 1987 and 1988. The proportion of streamflow contributed by Salt Slough (site 2) was much lower during 1986 than during subsequent drought years.

The sum of the streamflow measured at the upstream tributary sites was less than the streamflow measured at site 11 during 1986-88, indicating that unmeasured sources contributed more flow to the river than was withdrawn for irrigation. Sources of unmeasured flows include unmeasured tributaries originating in the Coast Ranges, unmeasured drain flows and irrigation-return flows, and ground-water discharge. Tributary sites accounted for 87 percent of the streamflow at site 11 in 1986, for 82 percent in 1987, and for 80 percent in 1988 (table 1). The volumes of unmeasured inflows to the river upstream of Vernalis were 862, 400, and 265 million m^3 for water years 1986, 1987, and 1988, respectively.

Daily measurements of specific conductance of water at sampling sites can provide an indirect measure of the dissolved solids in streamflow (Hem, 1985). Relations between specific conductance and dissolved solids at sites 1 through 11 were discussed by Clifton and Gilliom (1989). For the purpose of this report, specific-conductance data will be used as an indicator of dissolved-solids concentrations. Monthly mean specific conductance at site 11 is shown in figure 5 for the 1985-88 study period. Specific conductance at site 11 was lowest during the high-flow period and erratically increased to the highest values of the study period during the latter part of the 3-year low-flow period that followed the 1986 flood. The relation between flow and salinity at site 11 is discussed in detail by Kratzer and Grober (1991). Specific conductance at site 11 reflects contributions of dissolved solids and water from tributary streams represented by study sites, contributions from unmeasured sources, and withdrawals for irrigation. Tributaries that contribute proportionately more dissolved solids than water tend to increase the specific conductance at site 11; tributaries that contribute proportionately more water than dissolved solids tend to dilute dissolved-solids concentrations and correspondingly decrease the specific conductance at site 11.

The contributions of tributaries to the dissolved solids and specific conductance measured at site 11 were evaluated in two ways: by contribution to the dissolved-solids load transported past site 11, and by the effect that they have on the concentration of dissolved solids at site 11. For both evaluations, specific conductance data were used instead of dissolved solids because of the availability of daily measurements. Though there are slight differences between sites in the relation between dissolved solids and specific conductance, the results based on specific conductance are a reasonable representation of the proportional influences of tributaries on dissolved-solids concentrations. The evaluations are qualitative because of distortions in relations between sources and dissolved solids at site 11 caused by withdrawals of water at different points along the river. In reality, the dissolved solids from each different source are variably affected by withdrawals enroute to site 11. In the following evaluations, tributary sources are assumed not to be affected by withdrawals, and withdrawals affect only the estimates for unmeasured sources.

To evaluate the relative contributions of tributaries to the dissolved-solids load at site 11, equation 1 was used to compute the part of the specific conductance measured at site 11 that was attributable to the dissolved-solids load of each tributary or group of tributaries:

$$SC_{i/11} = (SC_i \bullet Q_i)/(Q_{11}) \tag{1}$$

where

$SC_{i/11}$ is specific conductance (μS/cm) at site 11 attributable to streamflow and dissolved solids from tributary i;

SC_i,Q_i are specific conductance (μS/cm) and streamflow (m^3/s) for tributary i; and

Q_{11} is streamflow (m^3/s) at site 11.

For a group of tributaries, the individual values of $SC_{i/11}$ for each stream are added together. In all computations, monthly mean values of streamflow and specific conductance were computed from daily values for use in equation 1. Figure 5 shows monthly mean specific conductance at site 11 and the proportions of the site 11 conductivity accounted for by the load of dissolved solids from each tributary or group of tributaries. The proportional contribution of unmeasured sources was estimated as the difference between specific conductance measured at site 11 and the sum of estimated contributions from tributary sources represented by study sites.

The estimated contribution of unmeasured sources represents the net result of a complex mixture of sources and withdrawals. The California Regional Water Quality Control Board, Central Valley Region, has identified about 100 withdrawals and more than 100 discharges in the study area (James and others, 1989). Although the overall annual volume of withdrawals and discharges generally is similar, the amount of dissolved solids removed from the river is greater than that returned through discharges because about one-half of the discharges come from dilute Sierran waters diverted above the study area on the east side of the San Joaquin Valley (Kratzer and others, 1987). This recycling of dissolved solids in the study area complicates the analysis of sources, especially during low-flow periods in the river when major diversion pumps in the San Joaquin River above the Tuolumne River divert most of the river flow (Kratzer and Grober, 1991). The amount and distribution of withdrawals causes distortions in the relations between tributary sources of dissolved solids and dissolved solids at site 11. The contribution of ground water also is significant, accounting for an estimated 5 to 8 percent of streamflow and 24 percent of dissolved-solids load to the river in October 1986 to September 1988 (Phillips and others, 1991).

Several key points are illustrated in figure 5:

- Except during high-flow conditions, the upper San Joaquin River (site 1) accounts for a small part of the dissolved-solids load at site 11.
- The three Sierra Nevada tributaries (sites 5, 8, and 10) also account for a small part of the dissolved-solids load at site 11 despite contributing most of the streamflow.
- Salt and Mud Sloughs (sites 2 and 4) and unmeasured sources of dissolved solids downstream of study sites contribute most of the dissolved solids to the river.
- At times, Salt and Mud Sloughs were the dominant sources of dissolved solids measured at site 11, and at other times, the unmeasured sources were collectively greater than Salt and Mud Sloughs combined.

The influence of tributary and unmeasured sources of inflow on the salinity of the San Joaquin River is distorted in some respects in figure 5, which is based on proportional contributions of dissolved-solids loads. This type of analysis ignores the significant and variable roles that different sources of water play in dilution. To address this issue, equation 2 was used to compute the estimated specific conductance at site 11 in the absence of streamflow or dissolved-solids loading from the same selected tributaries represented in figure 5.

$$SC_{11-i} = \frac{[(SC_{11}\bullet Q_{11})-(SC_i\bullet Q_i)]}{(Q_{11}-Q_i)} \qquad (2)$$

where

$SC_{11\text{-}i}$ is the estimated specific conductance (µS/cm) that would occur at site 11 in the absence of streamflow and loading from tributary site *i*;

SC_{11}, SC_i are the monthly mean specific conductances (µS/cm) measured at site 11 and site *i*, respectively; and

Q_{11}, Q_i are the monthly mean streamflows (m^3/s) measured at site 11 and site *i*, respectively.

Figure 6 shows the measured monthly mean specific conductance at site 11, compared to the estimated specific conductance that would occur at site 11 if streamflow and loading were eliminated from (1) Salt and Mud Sloughs (sites 2 and 4), (2) the Sierra Nevada tributaries (sites 5, 8, and 10), and (3) unmeasured sources (net result of unmeasured sources and withdrawals). Though complete elimination of streamflow from any of these three general sources of water is not a realistic possibility, the results in figure 6 indicate the sensitivity of specific conductance at site 11 to changes in different sources of streamflow as a result of the interplay of loading and dilution. For example, at the start of 1986, when measured specific conductance at site 11 was about 800 µS/cm (microsiemen per centimeter at 25° Celsius), complete elimination of streamflow from the Sierra Nevada tributaries would have caused specific conductance at site 11 to increase to about 2,000 µS/cm because of reduced dilution. Or, elimination of 50 percent of the streamflow from the Sierra Nevada tributaries would have resulted in about 1,400 µS/cm (measured value of 800 µS/cm, plus 50 percent of the 1,200 µS/cm change due to complete elimination). Alternatively, if streamflow and loading measured at sites 2 and 4 on Salt and Mud Sloughs were eliminated at the start of 1986, specific conductance at site 11 would have decreased from 800 to about 600 µS/cm because of the decreased dissolved-solids load. Figure 6 shows the high degree of sensitivity of salinity at site 11 to dilution by Sierra Nevada runoff and the variable and relatively equal roles of water and dissolved solids entering the river from the sloughs and unmeasured sources.

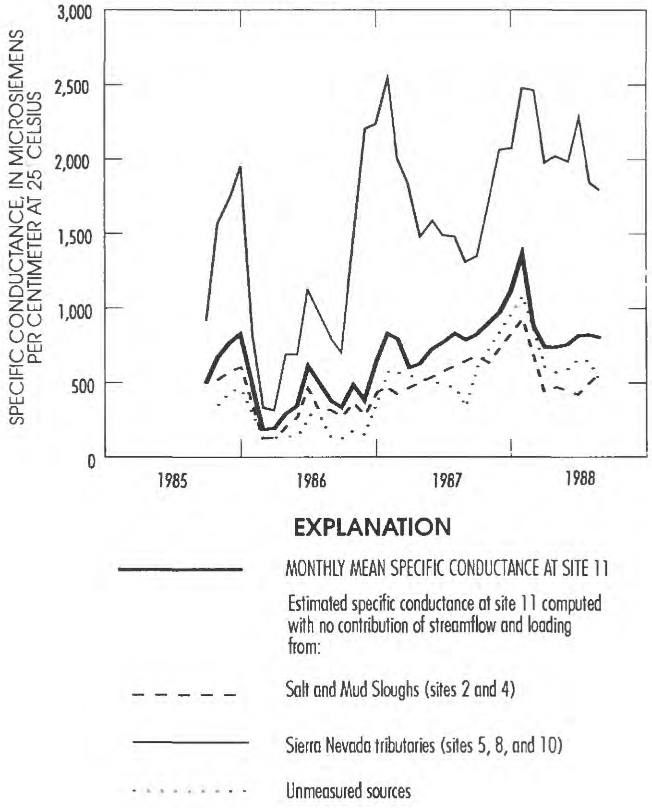

Figure 6. Monthly mean specific conductance of the San Joaquin River near Vernalis (site 11), compared to estimated specific conductance at the same site in the absence of selected tributary sources of streamflow and dissolved-solids load.

MAJOR-ION COMPOSITION

The major-ion compositions of water at key tributary sites and in the San Joaquin River at site 11 are illustrated with trilinear diagrams in figures 7-9. These diagrams facilitate the classification of major-ion chemistry by providing a means of distinguishing the dominant cations and anions at each site (Hem, 1985). The most commonly used classifications based on cation composition are waters with predominantly monovalent cations (sodium and potassium) and those with predominantly divalent cations (calcium and magnesium). On the basis of anion composition, waters are classified as primarily carbonate and bicarbonate (anions derived partially from solution of atmospheric carbon dioxide) or primarily sulfate and chloride (anions derived primarily from dissolution of solid-phase minerals in rocks, soils, and sediments).

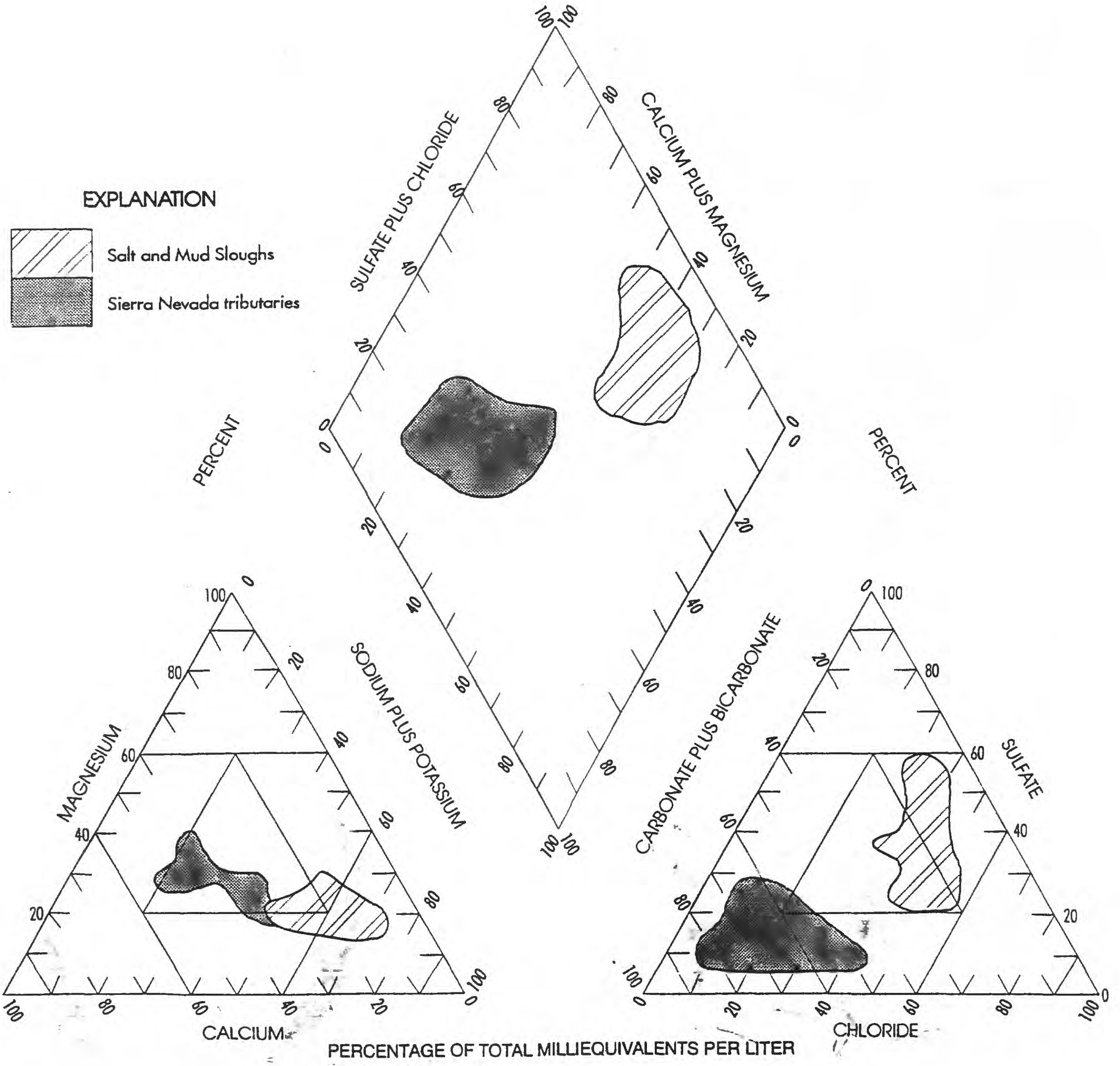

Figure 7. Major-ion composition of water from Salt and Mud Sloughs and from the Sierra Nevada tributaries.

Two distinct types of water can be distinguished among the tributary sites on the basis of major-ion composition (fig. 7): Salt and Mud Sloughs (sites 2 and 4) and the Sierra Nevada tributaries (sites 5, 8, and 10). Sierra Nevada streams have higher proportions of calcium and magnesium than sodium and potassium and higher proportions of carbonate plus bicarbonate than sulfate plus chloride. The two sloughs, in contrast, have higher proportions of sodium and potassium (primarily sodium) than calcium and magnesium, and higher proportions of sulfate plus chloride than carbonate plus bicarbonate. Major-ion compositions at sites 1 (fig. 8) and 11 (fig. 9) indicate that water from these sites is a mixture of water from the sloughs or similar sources and from Sierra Nevada runoff.

Major-ion compositions during the high-flow period differed from the low-flow period at sites 1 and 11 (figs. 8 and 9) because of the dominance of

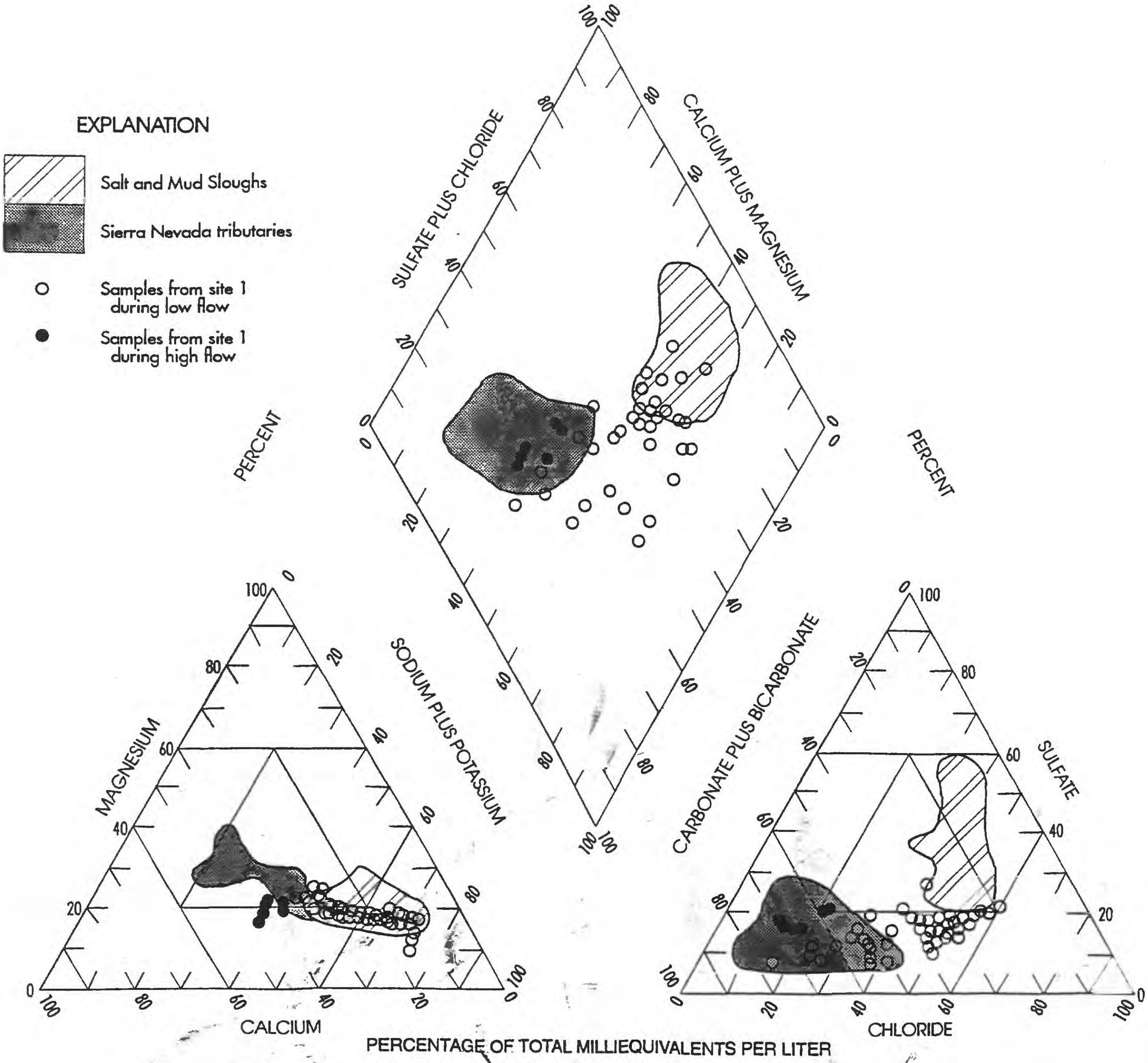

Figure 8. Major-ion composition of upper San Joaquin River (site 1) during low- and high-flow conditions.

Sierra Nevada runoff. Proportions of calcium, magnesium, bicarbonate, and carbonate were higher at these sites during the high-flow period; proportions of sodium, potassium, sulfate, and chloride were lower. Changes were similar, although more subtle, in the three Sierra Nevada tributaries during the high-flow period. Major-ion compositions of Salt and Mud Sloughs remained relatively constant during the entire study period.

CONCENTRATIONS AND SOURCES OF SUSPENDED SEDIMENT

Suspended-sediment concentrations and loads at site 11 peaked sharply at more than 600 mg/L (milligrams per liter) during the initial rise of the high-flow period during February 1986 (fig. 10). Despite higher peak flows in March 1986, high rates of suspended-sediment discharge were not sustained

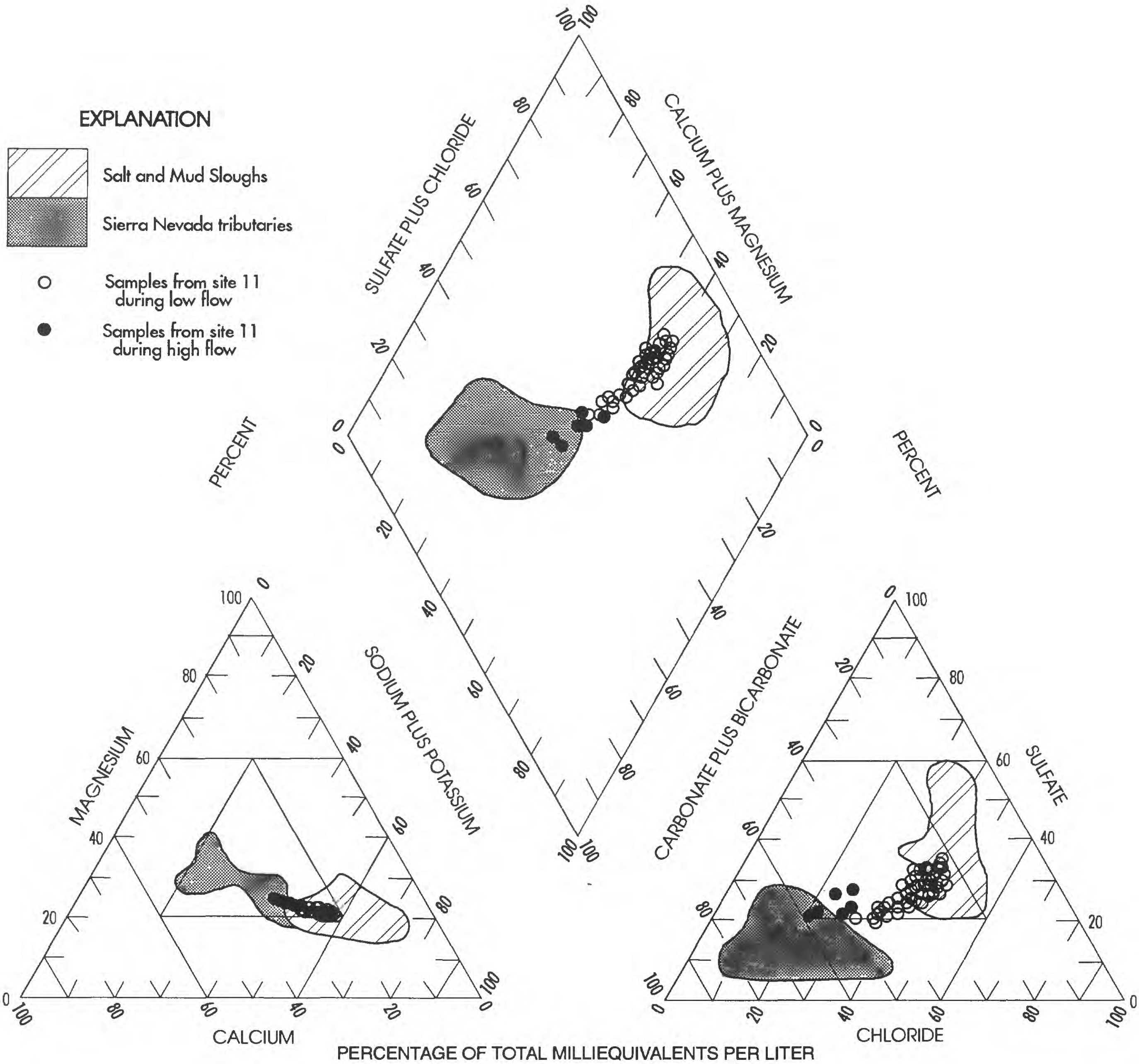

Figure 9. Major-ion composition of San Joaquin River near Vernalis (site 11) during low- and high-flow conditions.

because of low concentrations of suspended sediment in flood waters. The rapid, short-duration peak in suspended-sediment loads suggests a flushing of the channel system during the initial rise in February, followed by depletion of sediment supply later in the high-flow period.

During the low-flow period, concentrations and loads were fairly uniform, generally reaching the annual minimum in midwinter and the annual peaks in late spring or early summer (fig. 10). Daily mean suspended-sediment concentrations at site 11 were rarely greater than 200 mg/L during the study period and were often as low as 30 mg/L during the low-flow periods (Hunter and others, 1987, 1988a, 1988b; Mullen and others, 1989). Concentrations were highest during winter storms, especially in 1986, and during early summer irrigation seasons.

Sources of suspended-sediment loading to the river varied substantially during the study. The average loads from the Sierra Nevada tributaries were

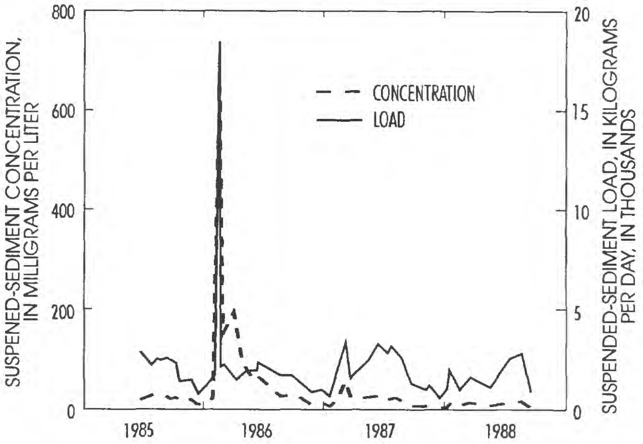

Figure 10. Concentrations and loads of suspended sediment for the San Joaquin River near Vernalis (site 11).

equivalent to 16 percent of the average load of the San Joaquin River near Vernalis (site 11) during the low-flow period despite contributing 68 percent of streamflow (table 2). The sediment load of the upper San Joaquin River (site 1) was equal to only 4 percent of the load at Vernalis. Salt and Mud Sloughs combined to equal 30 percent. Together, the average sediment loads from tributaries totaled only 50 percent of the load at Vernalis, indicating substantial additions of sediment from agricultural return flows and channel erosion between the tributary sites and site 11 at Vernalis.

During the high-flow period, a much greater proportional load came from the upper San Joaquin River (35 percent) than during the low-flow period, the Sierra Nevada tributaries contributed a similar proporional load (20 percent), and Salt and Mud Sloughs were less important sources (4 percent) (table 2). Overall, average sediment loads from tributaries totaled only 59 percent of the average load of the San Joaquin River near Vernalis during the high-flow period. As is evident for the low-flow period, the average sediment loads indicate substantial net gains in sediment load from unmeasured sources between study sites. Whereas such contributions during low-flow conditions probably are dominated by agricultural return flows, resuspension and erosion of sediment from flooded lands and channels probably are the main sources during high-flow conditions.

Table 2. Average proportional contributions of streamflows and suspended-sediment loads as percentages of the average streamflow and suspended-sediment load at San Joaquin River near Vernalis (site 11)

[Asterisk (*) indicates a tributary site]

Site No. (fig. 1)	Low flow		High flow	
	Streamflow	Suspended-sediment load	Streamflow	Suspended-sediment load
*1	4	4	42	35
*2	11	24	2	2
3	15	28	45	35
*4	3	6	1	2
*5	11	4	12	8
6	31	56	61	36
7	42	58	57	67
*8	26	5	27	7
9	74	108	94	108
*10	31	7	17	5
11	100	100	100	100

TRACE ELEMENTS

The preceding analysis of the distribution and sources of dissolved solids and sediment provides a background for understanding the distribution of trace elements in the San Joaquin River and its tributaries. Elements in dissolved phase respond to the same physical processes, such as streamflow and dilution, as other dissolved solids. Elements that occur primarily in particulate phases are most affected by sources and transport of sediment and other particulate matter in river water. Elements in both particulate and dissolved phases also may be affected by biological or chemical processes that alter their form and concentration in water. Based on the evaluation of partitioning, dissolved-phase and particulate-phase trace elements are assessed in two separate groups. The elements in both groups have varying degrees of potential significance to water quality of the San Joaquin River.

Trace-element partitioning was assessed by dividing the dissolved concentration of an element in a sample by its total recoverable concentration in the same sample and multiplying by 100 to express as a percentage. Table 3 summarizes trace-element concentrations and partitioning at each site. Analytical results less than detection limits were included to determine percentiles and medians, but were not used to compute partitioning. If the 25th percentile of concentrations was less than the detection limit for a particular element-site combination, no partitioning was computed. Trace elements present primarily in dissolved phases (generally greater than 50 percent dissolved) are arsenic, boron, lithium, molybdenum,

Table 3. Concentrations and partitioning of trace elements at sites 1-11, 1985-88

[All concentrations are total recoverable concentrations, in micrograms per liter; the detection limit (dl), in micrograms per liter, is in parentheses following the name of the element; NC indicates no calculation of partitioning was possible due to numerous samples less than detection limits. Asterisk (*) indicates a tributary site]

Site No. (fig. 1)	25th percentile	Median	75th percentile	Median percentage in dissolved phase	25th percentile	Median	75th percentile	Median percentage in dissolved phase
	Aluminum (dl=10)				Arsenic (dl=1)			
*1	610	980	2,050	1.7	3.0	5.0	8.0	88
*2	2,200	3,650	5,250	.2	4.0	5.0	6.0	67
3	1,650	2,900	4,400	.5	3.0	4.0	5.0	75
*4	1,400	2,400	3,500	.4	4.0	5.0	6.0	80
*5	230	330	560	2.8	1.0	1.0	2.0	100
6	1,450	2,350	3,970	.4	3.0	4.0	4.5	67
7	1,200	1,800	3,000	.7	3.0	4.0	4.0	75
*8	130	200	345	5.1	1.0	2.0	3.0	100
9	1,200	1,800	3,400	.5	2.0	3.0	4.0	75
*10	268	310	490	3.2	<1.0	<1.0	1.0	NC
11	950	1,300	2,400	.6	2.0	2.0	3.0	67
	Boron (dl=10)				Chromium (dl=1)			
*1	50	150	290	100	2.0	8.0	12.0	NC
*2	1,100	1,600	2,200	100	6.2	12.0	15.0	NC
3	645	1,200	1,600	100	7.0	10.0	14.8	NC
*4	2,000	2,900	3,400	100	6.0	12.0	21.0	NC
*5	20	30	48	100	2.0	6.0	9.0	NC
6	582	835	1,180	100	5.0	11.0	15.0	NC
7	400	840	1,100	100	5.0	9.5	13.0	NC
*8	20	30	40	100	1.0	5.0	9.0	NC
9	230	485	728	100	6.0	10.0	15.0	NC
*10	232	30	40	100	2.0	6.0	10.0	NC
11	50	390	488	100	4.0	7.0	10.0	NC
	Copper (dl=1)				Iron (dl=3)			
*1	5.0	5.0	7.2	25	900	1,600	3,150	1.6
*2	7.0	9.0	11.0	20	3,400	5,000	6,850	.3
3	6.0	7.0	9.0	27	2,700	4,200	5,700	.4
*4	6.0	8.0	12.0	25	1,900	3,400	4,980	.7
*5	3.0	4.0	6.0	33	490	740	1,00	8.6
6	6.0	8.0	10.0	20	2,320	3,450	5,650	.6
7	6.0	8.0	11.0	20	1,900	2,700	4,300	.6
*8	3.0	4.0	6.0	33	270	370	760	13.3
9	6.0	8.0	12.0	20	2,020	2,850	4,950	.6
*10	3.0	5.0	6.0	29	438	555	720	8.6
11	5.0	7.5	10.0	20	1,700	2,300	3,500	.8

and selenium, and trace elements presently predominantly in particulate phases (generally less than 50 percent dissolved) are aluminum, chromium, copper, iron, manganese, nickel, and zinc (table 3). Dissolved-phase elements of most potential significance to water quality in the San Joaquin River are arsenic, boron, molybdenum, and selenium. Particulate-phase elements of most potential significance are chromium, copper, nickel, and zinc. Each is discussed in more detail below. To the extent possible, concentrations of each element are discussed in relation to Federal water-quality criteria.

Table 3. Concentrations and partitioning of trace elements at sites 1-11, 1985-88--*Continued*

Site No. (fig. 1)	25th percentile	Median	75th percentile	Median percentage in dissolved phase	25th percentile	Median	75th percentile	Median percentage in dissolved phase
	Lithium (dl=10)				Manganese (dl=1)			
*1	<10	<10	10	NC	100	170	378	16
*2	30	40	50	90	330	440	565	47
3	20	30	40	95	242	290	408	28
*4	30	50	60	100	210	295	430	45
*5	<10	<10	<10	NC	60	80	110	26
6	10	20	30	88	192	240	338	20
7	10	20	30	98	188	225	280	26
*8	<10	<10	<10	NC	4.0	50	70	46
9	<10	20	20	90	138	180	272	19
*10	<10	<10	<10	NC	30	40	50	19
11	<10	10	20	NC	120	140	190	21
	Molybdenum (dl=1)				Nickel (dl=10)			
*1	2.0	5.0	11.5	100	4.0	6.0	9.0	38
*2	6.0	8.0	10.5	100	3.0	11.0	15.8	27
3	4.0	7.0	10.0	100	6.0	9.0	13.0	30
*4	7.0	10.5	14.0	100	10.0	14.0	20.2	29
*5	1.0	1.0	3.0	100	2.0	4.0	3.0	35
6	3.8	5.0	7.2	100	6.0	10.0	15.0	20
7	2.5	5.0	7.0	100	5.0	10.0	14.0	32
*8	<1.0	1.0	3.0	NC	2.0	4.0	7.0	71
9	1.8	3.5	5.2	94	6.0	10.0	18.0	20
*10	<1.0	1.0	2.0	NC	2.0	4.0	6.0	45
11	2.0	3.0	5.0	100	5.2	7.5	13.0	33
	Selenium (dl=0.1)				Zinc (dl=10 for total recoverable and 3 for dissolved)			
*1	0.2	0.3	0.6	100	<10	10	30	37
*2	5.1	9.4	15.4	99	20	20	30	40
3	1.6	6.2	9.9	99	15	20	30	30
*4	2.6	9.5	20.3	100	10	20	30	33
*5	<.1	.1	.2	100	<10	<10	20	43
6	1.5	3.8	6.4	100	10	20	30	30
7	1.3	3.3	4.8	97	10	20	30	50
*8	<.1	.1	.2	100	<10	10	20	40
9	.8	1.4	3.1	100	10	20	30	27
*10	<.1	<.1	.2	NC	<10	<10	20	55
11	.8	1.4	2.3	98	10	10	20	33

DISSOLVED-PHASE ELEMENTS

ARSENIC

Arsenic concentrations generally were low and consistent at all sites, and had dissolved forms accounting for medians of 67 to 100 percent. The highest median concentration of 5.0 μg/L was measured at sites 1, 2, and 4. The lowest median concentration of less than 1.0 μg/L was measured at site 10. Median concentrations of arsenic in the river decreased downstream from site 1 (5.0 μg/L), to sites 3, 6, and 7 (4.0 μg/L), to site 9 (3.0 μg/L), to site 11 (2.0 μg/L), because of dilution with water from Sierra Nevada tributaries (sites 5, 8, and 10), which had median arsenic concentrations of <1.0 to 2.0 μg/L.

Arsenic should not have adverse effects on water quality at the concentrations measured during this study. The U.S. Environmental Protection Agency aquatic-life criterion for trivalent arsenic (arsenic III) is 190 µg/L as a 4-day average, total-recoverable concentration (U.S. Environmental Protection Agency, 1986). Total-recoverable concentrations of all forms of arsenic are reported in this study and none of the measured concentrations approach the criterion. The Federal drinking-water criterion is 50 µg/L (U.S. Environmental Protection Agency, 1986) which also was not exceeded at any of the study sites.

BORON

Boron concentrations were highly variable between sites and over time at some sites, although dissolved forms accounted for a median of 100 percent at all sites. The highest median concentrations were in Salt Slough (1,600 µg/L) and Mud Slough (2,900 µg/L). Median concentrations in the river increased from 150 µg/L at site 1 to 1,200 µg/L at site 3 (downstream of Salt Slough), and then decreased to 835 µg/L at site 6 downstream of the Merced River inflow, and eventually decreased to 390 µg/L at site 11 after dilution by inflows from all three Sierra Nevada tributaries (sites 5, 8, and 10, all having medians of 30.0 µg/L boron).

Boron is an important water-quality concern in the San Joaquin River, primarily because of its effect on the quality of water for irrigation. The U.S. Environmental Protection Agency (1986) criterion for boron in irrigation water used over a long period of time is 750 µg/L. A criterion has not been established for aquatic life. The irrigation criterion of 750 µg/L was exceeded in more than 75 percent of the samples from Salt and Mud Sloughs, which are not directly used for irrigation. The irrigation criterion was exceeded in more than 50 percent of samples from sites 3, 6, and 7 on the San Joaquin River, a reach of river that is a source of irrigation water. Boron concentrations were less than 750 µg/L more than 75 percent of the time at sites 9 and 11.

MOLYBDENUM

Molybdenum concentrations generally were low and consistent at all sites, and had dissolved forms accounting for a median of 100 percent of the total recoverable concentration at all sites except site 9 (94 percent). As with boron, the median concentrations were highest in Salt Slough (8.0 µg/L) and Mud Slough (10.5 µg/L) and there was gradual dilution in the San Joaquin River from site 3 (7.0 µg/L) to site 11 (3.0 µg/L). The Sierra Nevada tributaries, which enter the San Joaquin River between sites 3 and 11, had median concentrations of 1.0 µg/L.

Although Federal water-quality criteria have not been established for molybdenum, the State of California has identified it as a water-quality concern in the San Joaquin River system. The State objectives are to not exceed monthly mean concentrations of 19 µg/L molybdenum in Salt and Mud Sloughs and in the San Joaquin River upstream of the Merced River inflow (site 6), or 10 µg/L in the San Joaquin River from the Merced River inflow to site 11 at Vernalis (California Regional Water Quality Control Board, Central Valley Region, 1991). These concentrations were not exceeded more than once at any of the study sites except Mud Slough, where 19 µg/L was exceeded in 12 percent of the samples.

SELENIUM

Selenium concentrations follow the same general pattern among sites as boron, and had dissolved forms accounting for medians of 97 to 100 percent of total recoverable concentration. The highest median concentrations were in Salt Slough (9.4 µg/L) and Mud Slough (9.5 µg/L). Median concentrations in the river increased from 0.3 µg/L at site 1 to 6.2 µg/L at site 3, downstream of Salt Slough, but decreased to 1.4 µg/L at site 11 after dilution by water from the Merced River (site 5; 0.1 µg/L), Tuolumne River (site 8; 0.1 µg/L), and Stanislaus River (site 10; <0.1 µg/L). Proportionately, selenium concentrations were diluted more between sites 3 and 11 than were arsenic, boron, and molybdenum.

The U.S. Environmental Protection Agency (1987) water-quality criteria for selenium are: (1) a 4-day average concentration of 5 µg/L, not to be exceeded more than once every 3 years on the average, and (2) a 1-hour average of 20 µg/L, not to be exceeded more than once every 3 years on the average. For the time scale and sampling frequency of this study, the 5 µg/L criterion is the most relevant for discussion. Median concentrations exceeded 5 µg/L in Salt Slough (9.4 µg/L), the San Joaquin River at site 3 (6.2 µg/L), and in Mud Slough (9.5 µg/L). In Salt Slough, selenium concentrations exceeded 5 µg/L in more than 75 percent of the samples. Selenium concentrations exceeded 5 µg/L in more than 25 percent of the samples from the San Joaquin River at site 6, even after dilution by the Merced River inflow. Thus, in Salt and Mud Sloughs and in the San Joaquin River between Salt Slough and the Merced River, selenium commonly exceeded the water-quality criterion. Even downstream of the Merced River, median concentrations of selenium in the San Joaquin River are greater than 2 µg/L until dilution by the Tuolumne River.

PARTICULATE-PHASE ELEMENTS

CHROMIUM

Chromium concentrations varied relatively little between study sites, having median total-recoverable concentrations ranging from 5.0 to 12.0 µg/L. At most sites, dissolved chromium probably was less than 10 percent of the total recoverable. Dissolved chromium was less than the detection limit of 1 µg/L in most samples from all sites.

The U.S. Environmental Protection Agency (1986) water-quality criteria for chromium specify 11 µg/L chromium IV as a 4-day average not to be exceeded more than once every 3 years. The criterion for chromium III, another form of chromium, is specified as a function of water hardness. Typical water hardness at the study sites ranges from about 50 mg/L as $CaCO_3$ (calcium carbonate) in the Sierra Nevada tributaries, to 400 mg/L as $CaCO_3$ in Salt and Mud Sloughs. At hardness values of 50, 200, and 400 mg/L as $CaCO_3$, the chromium III criteria would be 117, 365, and 644 µg/L, respectively. On the basis of this analysis, chromium IV is the only potential concern. Although total-recoverable chromium slightly exceeded 11 µg/L in more than one-half the samples from sites 2, 4, and 6, chromium species were not analyzed.

COPPER

Copper concentrations generally were low and consistent at all study sites, and had medians of 20 to 33 percent of total-recoverable copper in dissolved forms. Median total-recoverable concentrations ranged from 4.0 µg/L in the Merced and Tuolumne Rivers (sites 5 and 8) to 9.0 µg/L in Salt Slough. Compared with other elements, there was minimal dilution by Sierra Nevada tributaries.

The U.S. Environmental Protection Agency (1986) criteria for protection of aquatic organisms specify total recoverable copper concentrations that vary with water hardness. Over the range of hardness typical of the study sites (50, 200, and 400 mg/L as $CaCO_3$), the criteria would be 6.5, 21, and 39 µg/L copper, respectively, as 4-day averages not to be exceeded more than once every 3 years. Total-recoverable copper concentrations occasionally (less than 25 percent of samples) exceed hardness-based criteria in the Sierra Nevada tributaries when hardness decreases to substantially less than 50 mg/L $CaCO_3$. Dissolved copper concentrations were less than the criteria in all but one sample.

NICKEL

Nickel concentrations were relatively low and consistent at all study sites, and had medians of 20 to 71 percent of total-recoverable nickel in dissolved forms. Compared with chromium and copper, there was a greater contrast in nickel concentrations between Sierra Nevada water (medians of 4 µg/L in the Sierra Nevada tributaries) and Salt and Mud Sloughs (medians of 11.0 and 14.0 µg/L, respectively). Generally, the Sierra Nevada tributaries had a greater proportion of nickel in dissolved phases (35 to 71 percent) than did Salt and Mud Sloughs (27 and 29 percent), or the lower San Joaquin River at sites 6, 7, 9, and 11 (20 to 33 percent).

The U.S. Environmental Protection Agency (1986) water-quality criteria for protection of aquatic organisms specify total-recoverable nickel concentrations that vary with hardness. Over the range of hardness typical of the study sites (50, 200, and 400 mg/L as $CaCO_3$), the criteria would be 56, 160, and 274 µg/L, respectively, as 24-hour averages. Based on typical hardness values, total-recoverable nickel never exceeded the criteria at any of the study sites.

ZINC

Zinc concentrations also were relatively low and consistent, and had medians of 27 to 55 percent in dissolved phases. Median zinc concentrations were slightly higher than chromium, copper, or nickel concentrations at the same sites, but the same general pattern of higher median concentrations in Salt and Mud Sloughs (20.0 µg/L) and lower median concentrations in the Sierra Nevada tributaries (10.0 µg/L or less) prevailed.

The U.S. Environmental Protection Agency (1986) water-quality criterion for protection of aquatic organisms is a 24-hour average of 47 µg/L total recoverable zinc. Total-recoverable zinc concentrations occasionally exceeded 50 µg/L at all sites, but in substantially less than 25 percent of the samples.

PATTERNS AND TRENDS IN DISSOLVED SOLIDS, BORON, AND SELENIUM CONCENTRATIONS

Of the constituents investigated in this study, dissolved solids, boron, and selenium are of the greatest concern for the water quality of the San Joaquin River. General patterns and trends in these constituents observed in the San Joaquin River near Vernalis (site 11), provide a useful perspective on factors that affect the water quality of the river.

RELATIONS BETWEEN DISSOLVED SOLIDS, BORON, AND SELENIUM

Dissolved solids, boron, and selenium concentrations measured in the San Joaquin River at site 11 are positively correlated with each other and negatively correlated with the logarithm of streamflow (table 4), as determined by linear regression analyses. Concentrations are highest at the lowest flows and lowest at the highest flows, and vary little over the range of high flows from 200 to 1,000 m^3/s. This pattern reflects the dilution of dissolved solids, boron, and selenium that occurs at high flows as the proportion of water from dilute Sierra Nevada runoff increases.

Boron and selenium are positively and linearly correlated with dissolved solids. Dissolved-solids concentration explains 84 percent of the variation in boron concentrations and 54 percent of the variation in selenium concentrations. The addition of the logrithm of streamflow in multiple regression analyses, though significant at $\alpha=0.05$, only improves the variance explained from 84 to 86 percent for boron and 54 to 58 percent for selenium. The closer relation between dissolved solids and boron, compared with dissolved solids and selenium results partly because boron is closely associated with dissolved solids in most major sources of dissolved solids to the river, whereas selenium is most closely associated with dissolved solids in Salt and Mud Sloughs, which receive high-selenium tile drainwater. In addition, relative analytical variance is less for boron than for selenium. Because of the connection of boron and selenium with waters associated with Coast Range-derived soils and sediment, selenium concentrations are more highly correlated with boron than with dissolved solids.

Table 4. Linear correlations among dissolved solids, boron, and selenium concentrations and streamflow at San Joaquin River near Vernalis (site 11)

	Correlation coefficients (r)		
	Streamflow ($\log_{10}$)	Dissolved solids	Boron
Dissolved solids . .	-0.61		
Boron	-.50	0.92	
Selenium	-.37	.74	0.88

SEASONAL PATTERNS

Seasonal patterns were investigated for the 1985-88 study period. The correlation among dissolved solids, boron, and selenium is reflected by the same general seasonal patterns for all three in the San Joaquin River at site 11 (fig. 11). Each year, concentrations of all three constituents usually are highest during late winter to early spring, followed by lower concentrations in early summer, higher concentrations again in mid-to-late summer, and usually the lowest concentrations of the year in the autumn.

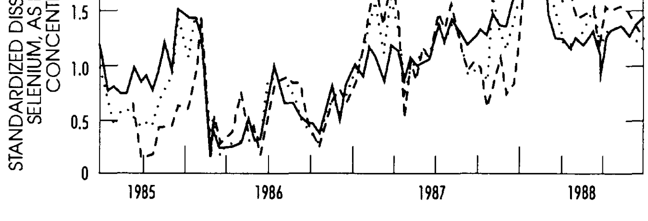

Figure 11. Patterns and trends in relative concentrations of dissolved solids, boron, and selenium in the San Joaquin River near Vernalis (site 11) during 1985-88.

These seasonal patterns in concentrations relate primarily to seasonal changes in the sources of water to the river. Four principal types of water enter the river: Sierra Nevada tributary inflows, surface irrigation-return flows, ground water, and subsurface agricultural drainwater. The Sierra Nevada tributaries (sites 5, 8, and 10) generally contribute 50 to 80 percent of the streamflow at site 11 (fig. 4). They tend to contribute lower percentages of streamflow in late summer to autumn and higher percentages during winter to early summer. In 1986, much of the Sierra Nevada runoff was measured at site 1 during the high-flow period (fig. 4). As indicated in figure 5, sites 5, 8, and 10 account for a low and relatively constant percentage of the dissolved-solids load to the San Joaquin River.

Surface irrigation-return flows follow the summer irrigation season, and generally peak between April and September. For example, figure 4 shows the total contribution of unmeasured sources of water to the San Joaquin River. With the assumption that ground water does not vary substantially compared to surface irrigation-return flows, most of the seasonal pattern in unmeasured inflows indicated in figure 4 is believed to be due to surface irrigation-return flows. Clifton and Gilliom (1989) reported that water entering the river between sites 6 and 7 was about 73 percent surface irrigation-return flows and 27 percent ground water in October 1986. On an annual basis, Phillips and others (1991) estimated that ground water could account for 5 and 8 percent of total river flow in 1987 and 1988, respectively. Overall, the combination of water entering the San Joaquin River from all sources located downstream of tributary sites 1, 2, 4, 5, 8, and 10 was estimated to be about 20 percent of the total river flow at site 11 during 1985-87 (Clifton and Gilliom, 1989). Synoptic studies of combined surface and subsurface irrigation-return flows between sites 6 and 7 during October 1986 and June 1989, indicated flow-weighted mean specific conductances of 408 and 792 µS/cm, respectively (Phillips and others, 1991). These return flows include several subsurface drainage systems that discharge water with relatively high salinity (about 2,000 µS/cm), but with selenium usually less than 5 µg/L.

Little is known about seasonal patterns in ground-water inflow to the San Joaquin River. Although seasonal patterns probably occur in response to irrigation and ground-water pumping, ground-water inflow is much less variable than other sources. According to 1989 data, ground water flowing into the river had relatively high salinity and boron, but low selenium (Phillips and others, 1991). Water samples from 24 observation wells installed at 3 sites along the river, including study sites 6 and 7, indicate that the average composition of ground water flowing into the river is characterized by specific conductance of 2,230 µS/cm, boron of 1,321 µg/L, and selenium of 0.9 µg/L (Phillips and others, 1991).

Discharges from subsurface agricultural drainage systems to Salt and Mud Sloughs cause one of the most significant seasonal patterns in dissolved solids, boron, and selenium loading to the San Joaquin River. Figure 12 shows the seasonal distribution of flows and loads of dissolved solids, boron, and selenium from the Grasslands drainage area (95,000 acres) that contributes most subsurface tile drainwater to the river. In general, the seasonal patterns of dissolved solids, boron, and selenium loads are similar and correspond closely to tile-drain flows from the Grasslands drainage area. As with the pattern in dissolved solids, boron, and selenium concentrations in the San Joaquin River at site 11 (fig. 11), the loads are highest during late winter to early spring, followed by lower loads in early summer, higher loads again in mid-to-late summer, and usually the lowest loads of the year in autumn, after growing season irrigation and before preirrigation.

The significance to the San Joaquin River of the loading of dissolved solids, boron, and selenium from the Grasslands drainage area is evident by comparison of average 1984-88 loads from the drainage study area (from Pickett and Kratzer, 1988) to the loads in the San Joaquin River near Vernalis. During low-flow conditions from 1985 to 1987, studied by Clifton and Gilliom (1989), the dissolved-solids load averaged 2,780,000 kg/d at site 11, compared to 544,000 kg/d from the drainage area. Selenium loads averaged 9 kg/d at site 11 compared to 12.5 kg/d from the drainage study area. Clifton and Gilliom (1989) did not make similar load estimates for boron. The data indicate that the Grasslands drainage area is an important, but not dominant, source of dissolved solids to the river, and the dominant source of selenium to the river. The data suggest that there may be a loss of selenium between the drain inflows and site 11 due to withdrawals or other losses. However, considering the possibilities of estimation errors, the loads may actually be similar.

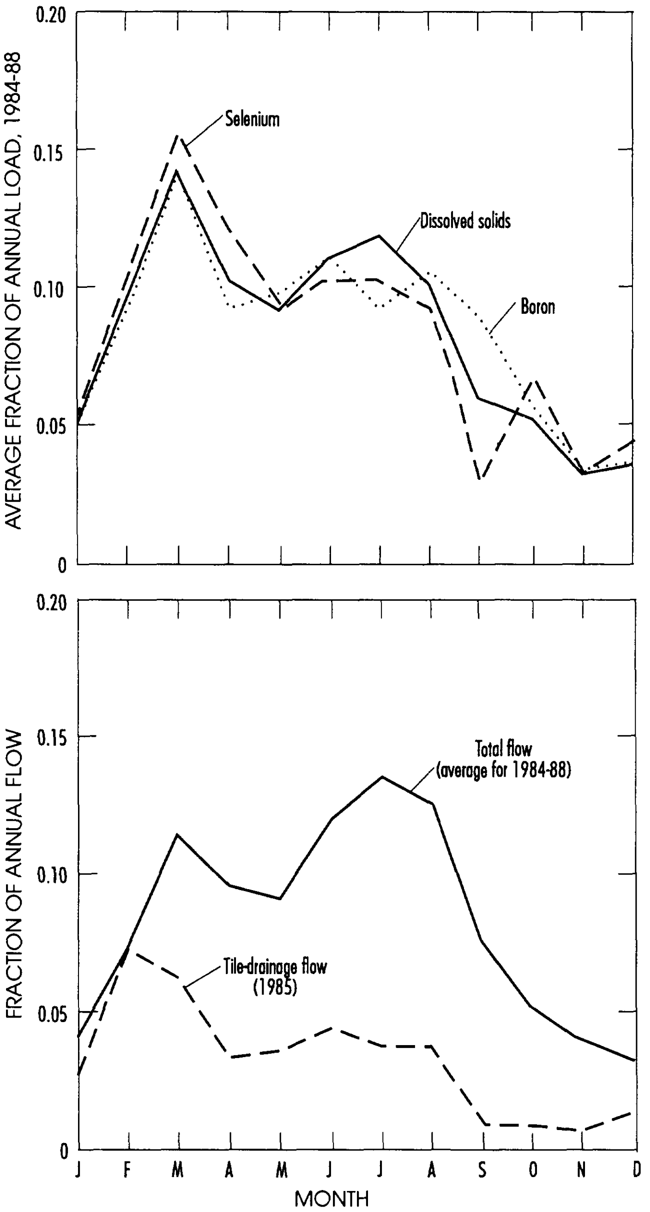

Figure 12. Seasonal distributions of flows and loads of dissolved solids, boron, and selenium from the Grasslands drainage area (based on data summarized in California State Water Resources Control Board, 1987 and Pickett and Kratzer, 1988)

SUMMARY AND CONCLUSIONS

This report provides an overview of selected hydrologic and water-quality conditions in the San Joaquin River and its major tributaries, which were studied during 1985-88 in response to concern about adverse effects of agricultural drainwater on the river.

The 1985-88 study period included hydrologic extremes throughout most of central California. During 1986, flooding affected much of the San Joaquin Valley. Drought conditions prevailed during 1987 and 1988. Except for an 11-month period during and after the 1986 flood, streamflows during the study period generally were less than median streamflows for 1975-88. Annual combined streamflow from the Sierra Nevada tributaries (the Merced, Tuolumne, and Stanislaus Rivers) comprised 56 to 69 percent of the annual streamflow of the San Joaquin River near Vernalis during 1986-88. Combined streamflow from Salt and Mud Sloughs comprised 6 to 19 percent of annual streamflow at Vernalis, and streamflow from the upper San Joaquin River comprised 2 to 25 percent of the streamflow at Vernalis; the highest value was for the 1986 flood. Unmeasured sources of water from irrigation-return flows and ground water accounted for 13 to 20 percent of the annual streamflow at Vernalis.

Except during high-flow conditions, the upper San Joaquin River and the Sierra Nevada tributaries contribute a small part of dissolved-solids loading to the San Joaquin River. Salt and Mud Sloughs and unmeasured sources of water, which consist mainly of irrigation-return flows and ground water, contribute most of the dissolved-solids load measured in the San Joaquin River near Vernalis. Though the Sierra Nevada tributaries contribute little dissolved-solids loading, they greatly affect dissolved-solids concentrations in the San Joaquin River through dilution.

Two distinct types of water with different major-ion compositions can be distinguished among study sites. Sierra Nevada tributaries are dominated by calcium and magnesium and by carbonate plus bicarbonate. Salt and Mud Sloughs are dominated by sodium and sulfate plus chloride. Other sites had various mixtures of these two water types.

Suspended-sediment concentration in the San Joaquin River near Vernalis peaked sharply at more than 600 milligrams per liter during February 1986. During low-flow conditions, concentrations and loads were fairly uniform, having highest concentrations during the early summer irrigation season. During both low-flow and high-flow periods, average sediment loads from tributaries studied totaled substantially less than the total load of the San Joaquin River near Vernalis, indicating substantial additions of suspended sediment from irrigation-return flows and from erosion and resuspension of sediment from channels and flooded areas.

Trace elements present primarily in dissolved phases are arsenic, boron, lithium, molybdenum, and selenium. Boron and selenium are the trace elements of greatest importance to water quality in this study area. Trace elements present primarily in particulate phases in the San Joaquin River are aluminum, chromium, copper, iron, manganese, nickel, and zinc; none of these are likely to cause significant water-quality problems in the river.

Boron and selenium concentrations are highest in Salt Slough (medians of 1,600 and 9.4 micrograms per liter) and Mud Slough (medians of 2,900 and 9.5 micrograms per liter), and decrease downstream in the San Joaquin River as dilution occurs. Boron concentrations exceeded the irrigation water-quality criterion of 750 micrograms per liter more than 50 percent of the time in the San Joaquin River at sites 3, 6, and 7. Selenium concentrations exceeded the aquatic-life water-quality criterion of 5 micrograms per liter more than 50 percent of the time in Salt and Mud Sloughs and in the San Joaquin River at site 3, and more than 25 percent of the time in the San Joaquin River at site 6, just downstream of the Merced River inflow.

Dissolved solids, boron, and selenium concentrations measured in the San Joaquin River near Vernalis (site 11) are positively correlated with each other and negatively correlated with streamflow, reflecting their common sources and dilution during high streamflows. Concentrations of dissolved solids, boron, and selenium usually were highest during late winter to early spring, followed by lower concentrations in early summer, higher concentrations again in mid-to-late summer, and the lowest concentrations of the year in autumn. The seasonal patterns in dissolved solids, boron, and selenium concentrations generally correspond to the seasonal patterns in the inflow of subsurface tile drainwater to Salt and Mud Sloughs. The tile drainage is one of the most significant sources of dissolved solids and the most significant source of selenium to the San Joaquin River.

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GPO 584-140, 1952M/19069