SOURCES AND CONCENTRATIONS OF DISSOLVED SOLIDS AND SELENIUM IN THE SAN JOAQUIN RIVER AND ITS TRIBUTARIES, CALIFORNIA, OCTOBER 1985 TO MARCH 1987

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

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CONVERSION FACTORS

For readers who may prefer to use inch-pound units rather than metric (International System) units, the conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
ha (hectare)	2.471	acre
kg (kilogram)	2.205	pound
kg/d (kilogram per day)	2.205	pound per day
km (kilometer)	0.6214	mile
m/km (meter per kilometer)	5.280	foot per mile
mm (millimeter)	0.03937	inch
m/s (meter per second)	3.281	foot per second
m^3 (cubic meter)	35.31	cubic foot
m^3/s (cubic meter per second)	35.31	cubic foot per second

Selenium concentrations are given in micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to 1 milligram per liter (mg/L). Micrograms per liter is the equivalent of "parts per billion."

Abbreviations used:

µS/cm	microsiemen per centimeter at 25 degrees Celsius
µm	micrometer

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ABSTRACT

Sources and concentrations of dissolved solids and selenium in the San Joaquin River and its tributaries, California, were assessed by a mass-balance approach to determine the effects of tile-drain water and irrigation-return flows on the river. The study included low-flow periods from October 1985 to mid-February 1986 and mid-May 1986 through March 1987, and a high-flow period from mid-February to mid-May 1986. During the combined low-flow period, the dissolved-solids load from eastside tributaries and the upper San Joaquin River accounted for only 18 percent of the total load at Vernalis, located farthest downstream, even though they accounted for 71 percent of streamflow. Salt and Mud Sloughs contributed 40 percent of the dissolved-solids load but only 9 percent of streamflow. Unmeasured sources of dissolved solids contributed about 42 percent of the total load during low flow. In contrast, Salt and Mud Sloughs, which receive most of the tile-drain water that enters the river, contributed almost 80 percent of the total selenium load to the river, and loading from unmeasured sources was minimal. Dissolved-solids concentrations were highest in Salt and Mud Sloughs and decreased downstream with dilution from eastside tributaries. Selenium concentrations also were highest in Salt and Mud Sloughs. The U.S. Environmental Protection Agency's 4-day average aquatic-life criterion of 5 micrograms per liter of selenium was exceeded in more than 60 percent of the samples from the sloughs and in about 20 percent of the samples from the San Joaquin River, just downstream of the Merced River.

INTRODUCTION

High concentrations of selenium in subsurface tile-drain water from agricultural areas in the western San Joaquin Valley, California, have adversely affected waterfowl and fish where the drain water has been impounded (Ohlendorf and others, 1986a and 1986b; Hamilton and others, 1986). Previous studies have addressed the distribution of selenium and other elements in drain water and ground water of the western San Joaquin Valley (Deverel and others, 1984; Presser and Barnes, 1984 and 1985; Neil, 1986; Deverel and Millard, 1988). Tile-drain water from about 31,000 ha of agricultural land in the western valley is discharged into the San Joaquin River or its tributaries (California State Water Resources Control Board, 1987). In addition, irrigation-return flows from extensive areas of farmland in the western and eastern parts of the valley flow into the river. There is concern that selenium, dissolved solids, and other contaminants in agricultural wastewaters may adversely affect the water quality of the river.

Compared to other rivers in the United States and throughout the world, the San Joaquin River has among the highest concentrations of total selenium. Data for numerous rivers throughout the world were reviewed by Cutter (1989). Excluding the San Joaquin River and one Belgian river, data for more than 30 rivers indicated that all had concentrations less than 0.5 μg/L. Even near its mouth, where concentrations are lowest, the San Joaquin River frequently exceeds 1 μg/L, more than double the concentration in most rivers.

This report describes the results of a study to assess the sources and concentrations of dissolved solids and selenium in the San Joaquin River and its tributaries. A mass-balance approach is taken to evaluate sources of loading. Streamflow, which was recorded continuously at all study sites, can be assessed most accurately and is evaluated first. Dissolved-solids loads at study sites can be calculated directly for individual measurements of flow and concentration or estimated reliably from streamflow and continuously recorded specific-conductance measurements. Selenium loads also can be computed directly for points in time when samples were collected, or can be estimated from continuous streamflow and specific-conductance data. Selenium loads are the most difficult to estimate indirectly because of greater natural and analytical variability at trace levels, and because selenium concentrations are not as closely correlated with specific conductance as are dissolved solids.

Two types of mass-balance analysis were applied to each of streamflow, dissolved solids, and selenium. Total loads were estimated for each site for low- and high-flow periods to evaluate general patterns. In addition, measured loads on individual sampling dates were used to compute more accurate instantaneous mass balances for the purpose of assessing changes in loads between study sites. The mass-balance approach allows contributions of selenium loads from different sources to be readily assessed in relation to contributions of streamflow and dissolved solids and forms the basis for understanding the distributions of dissolved-solids and selenium concentrations in the river system.

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.

STUDY AREA

The San Joaquin Valley has hot, dry summers and cool, wet winters. Although the average annual precipitation on the valley floor is less than 250 mm, the Sierra Nevada has as much as 2,030 mm of precipitation, mostly as snow (Rantz, 1969). The major land use in the valley is agriculture, and an extensive network of storage reservoirs and canals provides the valley with irrigation water throughout most of the year.

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 are low, ranging 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, the river generally has intermittent streamflow and often river water does not reach Mendota Pool near Mendota. In the next 108 km between Mendota and study site 1, the river also has intermittent streamflow, except for a reach of several kilometers just downstream of Mendota, in which flow is perennial. Streamflow in the remaining 96 km between Stevinson, site 1, and site 11, near Vernalis, is perennial and increases downstream as tributaries and irrigation-return flows enter the river. Inflows to the river come from surface runoff and subsurface drain water from irrigated areas, ground water, and runoff from the Sierra Nevada. During high-flow periods, a greater proportion of river water is 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 at the San Joaquin River near Stevinson (site 1). During low-flow conditions, most water reaching site 1 is irrigation-return flow, but during high-flow periods most of the water is Sierra Nevada runoff.

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

The three major eastside tributaries that originate in the Sierra Nevada, with a combined drainage area of about 1 million ha, 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). 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.

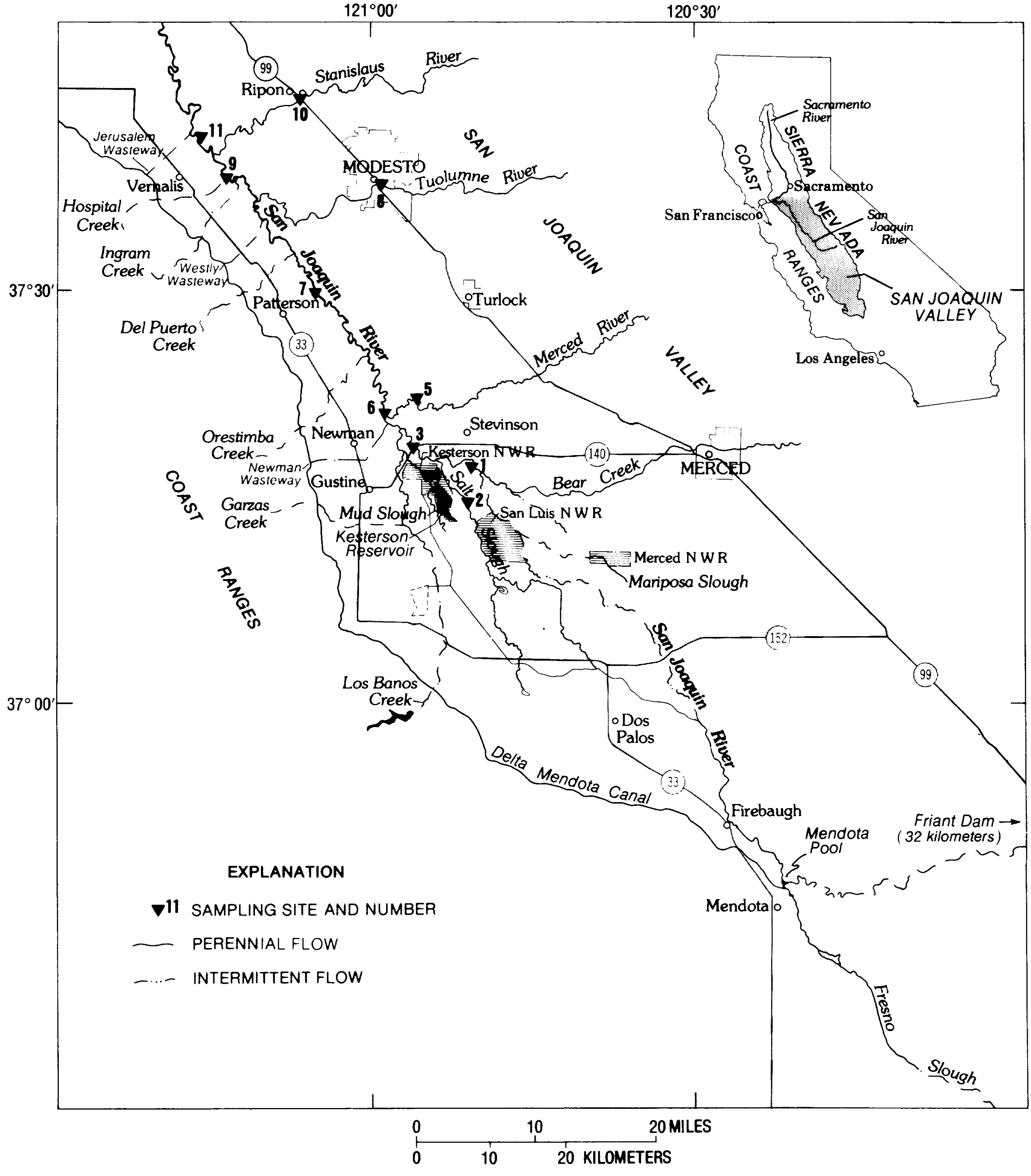

FIGURE 1. Location of sites sampled.

Sites downstream of site 1 on the lower San Joaquin River are distributed between the five major tributaries. Fremont Ford Bridge (site 3) is downstream of Salt Slough. Newman (site 6) is downstream of Mud Slough and the Merced River. Patterson (site 7) is downstream of Newman. Maze Road (site 9) is downstream of the Tuolumne River. Vernalis (site 11) is downstream of the Stanislaus River and upstream of the tidal backwater influence of the delta.

METHODS OF DATA COLLECTION AND ANALYSIS

Field and Laboratory

Water samples for dissolved solids and selenium analyses were collected twice monthly at all sites from October 1985 to June 1986. At all sites except Salt Slough, Mud Slough, and Vernalis, sampling frequency was reduced to monthly from July 1986 to March 1987. River stage and specific conductance were monitored by automatic recording instrumentation on a continuous basis at each site. Specific-conductance data at site 6 were not used in this report because the point samples collected using the automatic samplers did not adequately represent the cross section. Streamflow was measured at the same time water samples were collected, using procedures described by Buchanan and Somers (1969). Additional specific-conductance measurements were made at the same time water samples were collected, using an Extech[1] specific conductance meter, which was field calibrated using standards from U.S. Geological Survey laboratories. The measurements of streamflow and specific conductance made at the time of sampling were used to define the relation between river stage and streamflow and to determine the accuracy of automatic recording instrumentation for measuring specific conductance.

Depth-integrated, discharge-weighted, composite water samples for chemical analyses were collected at each site using D77 and DH48 samplers and standard U.S. Geological Survey methods (Guy and Norman, 1970; Brown and others, 1970). All equipment used to collect water for selenium analysis was prerinsed with 5 percent hydrochloric acid, distilled water, and large quantities of native water at each site. Equipment used was constructed of plastic, glass, or stainless steel. Samples for dissolved-solids and dissolved-selenium analyses were filtered immediately after collection using 0.45-µm membrane filters. Samples for analyses of total recoverable selenium were not filtered.

Total recoverable and total dissolved-selenium concentrations were analyzed in the U.S. Geological Survey laboratory in Sacramento using hydride generation and atomic absorption spectrometry (Fishman and Bradford, 1982; Fujii and others, 1988). A median of 98 percent of the total recoverable selenium in the samples was dissolved, and the two types of analyses were not significantly different (α=0.05). Particulate forms of selenium thus were a small proportion of selenium in the samples. All selenium concentrations discussed in this report are of dissolved forms, which also accurately represent total recoverable selenium.

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

Selenium speciation data for samples collected during this study at site 11 show that most of the selenium was in the selenate form (Dr. Gregory Cutter, Old Dominion University, Norfolk, Virginia, written commun., 1987), which is the most soluble and mobile form of selenium in the oxic and generally alkaline conditions of the San Joaquin River. For 13 samples collected throughout the second half of the study period, selenate accounted for 54 to 97 percent of the total selenium.

Quality-control procedures for selenium analysis included analyses of duplicate samples, standard reference samples, and blanks run after every six samples. The median difference between 28 duplicate samples with concentrations between 0 to 1 µg/L was 0.00 and ranged from -0.10 to 0.20 µg/L. The differences and the mean of duplicates were not correlated. The within-laboratory standard error of analysis at a 95-percent confidence interval was 0.1 µg/L at 0.5 µg/L, based on analyses of 57 reference samples containing 0.5 µg/L of selenium, and 1.0 µg/L at 9.8 µg/L, based on analyses of 39 reference samples containing 9.8 µg/L of selenium.

Analysis of Streamflow Sources and Constituent Loadings

Streamflow sources and constituent loadings were evaluated by two approaches: (1) computation of total streamflow and loads of dissolved solids and selenium at each site, and (2) computation of mass balances between all sites for individual sampling events. Both approaches were applied to low-flow and high-flow periods.

Estimation of Total Streamflow and Loads

Total streamflow that occurred at each site during the study period was computed directly from daily mean flows determined from continuous hourly records. Dissolved-solids and selenium loads were estimated from daily mean streamflows and daily mean specific conductances by using regression relations developed for each site.

The regression relations for estimating daily mean dissolved-solids and selenium loads were developed from measurements of streamflow, specific conductance, and concentrations of dissolved solids and selenium that were made monthly or twice monthly for each site. Thirty-seven samples were collected at sites 2, 4, and 11; 27 samples were collected at the remaining sites. Two sets of regression relations were developed for each site. The first set was developed from all samples at each site and was used to estimate loads during the high-flow period. A second set was developed only from samples collected during the low-flow period and was used to estimate loads only during the low-flow period. Initial analyses showed that almost all data should be log-transformed to achieve acceptable residuals.

Generally, a multiple-regression relation with two explanatory variables--the natural logarithms of streamflow and specific conductance--minimized estimation errors for dissolved solids and selenium loads. For some sites, specific conductance was not a significant (α=0.05) explanatory variable for selenium load; and for most sites, occasional periods of record for specific conductance were missing. In such instances, daily loads were estimated from the regression relation between loading and streamflow alone.

Mass Balances for Sampling Events

Computed totals of streamflow and constituent loadings for low- and high-flow periods allow useful generalizations about the magnitude of different sources to the river system. The uncertainties associated with estimating constituent loadings from the regression relations make it difficult to analyze within-reach gains or losses of streamflow or loads that occur in reaches between study sites. An alternative approach was used to estimate these within-reach changes. A mass balance was computed based on each set of water-chemistry samples collected at the 11 sites. The mass balance was computed for water at each site that would arrive at Vernalis, the farthest downstream site, at the same time as water from all the other sites.

Streamflow was evaluated first. Because the traveltime of water flowing to Vernalis is different for each of the 10 upstream sites, traveltimes were computed for each site from estimated velocities in the stream cross section:

$$T_i=(D/V_i)\cdot K_1, \qquad (1)$$

where

T_i is traveltime for the ith day, in days;

D is distance to Vernalis, in kilometers;

V_i is mean velocity for the ith day, in meters per second; and

K_1 is a unit conversion factor of 0.0116.

The value of V_i was computed from daily mean streamflow by using the results of a regression relation for each site between measured instantaneous velocity and the logarithm of instantaneous streamflow for the cross section. V_i at site 6 was determined from average velocities at sites 3 and 7. The number of samples used for the regression at each site ranged from 11 to 71. Two to four outliers for sites 2, 3, 8, and 9, and 10 outliers for site 1 were removed because they showed decreasing velocities with increasing flows during the high-flow period as a result of changing controls or backwater effects. Their removal from the analysis increased the significance of the regression at these sites.

Traveltimes estimated from the regression relations for each site are not appreciably different from traveltimes determined from a July 1987 time-of-travel study using fluorescent dye. The traveltime from site 6 to site 11 computed by equation 1, using the measured instantaneous streamflow of 21 m^3/s

on July 20, was 2.38 days. This compares to 2.33 days measured in the time-of-travel study for the same time period. The traveltime on July 21 from site 7 to site 9 was estimated at 1.23 days by equation 1, compared to 1.25 days determined from the time-of-travel study. Median traveltimes for each site are given in table 1.

The streamflow data were adjusted backward in time (lagged) for each site according to computed traveltimes, thus registering all data to Vernalis (site 11) time. After this adjustment, the sum of streamflows on the upper San Joaquin River and on major tributaries to Vernalis, sites 1, 2, 4, 5, 8, and 10, would equal streamflow at Vernalis if there were no within-reach gains or losses of flow between sites, errors in measurement, or short-term variations in flow between these sites and Vernalis. Similarly, any other combination of upstream and downstream sites would be additive if there were no within-reach gains or losses. Conversely, the difference between additive upstream sites and a downstream site can be used to indirectly assess within-reach unmeasured sources of water. Comparison of hydrographs of the lagged flow data showed that streamflow peaks generally occurred at the same time at each site, thus confirming that the hydraulic behavior of the system was reasonably represented by the approach taken.

Dissolved-solids and selenium loading were then calculated from the lagged streamflow data by equation 2 for each site and sample date.

$$L = C \cdot Q \cdot K_2, \tag{2}$$

where

L is dissolved-solids or selenium load, in kilograms per day;

C is dissolved-solids concentration, in milligrams per liter, or selenium concentration, in micrograms per liter;

Q is streamflow, in cubic meters per second; and

K_2 is a unit conversion factor of 86.4 for dissolved solids and 0.0864 for selenium.

Dissolved-solids or selenium loads computed by equation 2 from the lagged streamflows are additive in the same way that the streamflows are additive. Thus, within-reach gains or losses of dissolved solids or selenium can be assessed.

Ideally, samples for dissolved-solids and selenium analyses would have been collected at each site before samples were collected at Vernalis by an amount of time equal to the traveltime between the site and Vernalis. However, logistical constraints prevented this. Instead, the order of site sampling during each sampling trip generally was matched to the order of traveltimes. Normally, there was no more than a 1- to 2-day difference between samples collected at Vernalis and at the other sites. The assumption was made that dissolved-solids and selenium concentrations were constant at each site during the 1- to 2-day period between the actual sampling date and the date at which the lagged streamflow data were measured.

TABLE 1.--*Traveltime and distance to Vernalis during the low-flow period*

Site No.	Site name	Median traveltime (day)	Distance (kilometer)
1	San Joaquin River near Stevinson	2.86	97.2
2	Salt Slough at State Highway 165	2.65	97.3
3	San Joaquin River at Fremont Ford Bridge	2.76	84.6
4	Mud Slough near Gustine	3.52	92.7
5	Merced River near Stevinson	2.88	80.6
6	San Joaquin River near Newman	2.20	73.4
7	San Joaquin River near Patterson	1.17	42.3
8	Tuolumne River at Modesto	.98	45.0
9	San Joaquin River at Maze Road Bridge	.16	7.4
10	Stanislaus River at Ripon	.70	28.0
11	San Joaquin River near Vernalis	0	0

The assumption of constant dissolved-solids and selenium concentrations for 1- or 2-day periods was tested using daily specific-conductance data. This analysis is based on a second assumption that the variability of specific conductance is similar to that of dissolved solids and selenium at each site. Certainly, this second assumption is true for dissolved-solids concentration, which is highly correlated with specific conductance ($r^2 \geq 0.80$; $\alpha=0.05$) at all sites. The assumption that selenium varies in a manner similar to specific conductance is less valid but adequate. Selenium concentrations were correlated with specific conductance ($r^2=0.34$ to 0.68; $\alpha=0.05$) at sites 2, 3, 6, 7, 9, and 11. For sites 2, 3, 4, and 6 where selenium was highest, coefficients of variation were respectively 0.38, 0.66, 0.44, and 0.58 for specific conductance and 0.66, 0.87, 0.96, and 0.73 for selenium. Thus, selenium is somewhat more variable, which is at least partly due to greater measurement error.

As an extreme test of variability within 1- to 2-day periods, the difference was computed between specific-conductance measurements made 3 days apart using 212 to 547 measurements at each site. The median difference ranged from 3.8 to 9.9 percent among the 11 sites. This should be a conservatively high estimate of the variability of dissolved solids within 1- to 2-day periods and may approximate the variability of selenium concentrations in the absence of analytical error. Thus, the assumption of constant concentrations during the 1- to 2-day periods that sometimes occurred between actual sampling and the date at which lagged streamflows were measured is not strictly valid but probably is not a severe problem.

STREAMFLOW

Streamflow is a major factor determining the quantity of a constituent transported through a river system. Daily mean streamflow at Vernalis during October 1985 to March 1987 shows three relatively distinct flow regimes (fig. 2). Low-flow periods occurred from October 1985 to mid-February 1986 and from mid-May 1986 through March 1987, during which daily mean streamflow was less than 280 m^3/s at Vernalis. These two periods are combined in subsequent analyses and discussed as the low-flow period. The high-flow period occurred from mid-February to mid-May 1986, which included the rising waters of a major flood and the recession to 280 m^3/s at Vernalis.

Monthly mean streamflows at Vernalis during the low-flow period prior to mid-February 1986 were in the 11th to 33d percentiles relative to the long-term monthly means for 1975-87 (fig. 2). During the high-flow period, monthly mean streamflows were in the 76th to 89th percentiles relative to monthly mean streamflows for 1975-87. Although the initial peaks of the flood occurred in

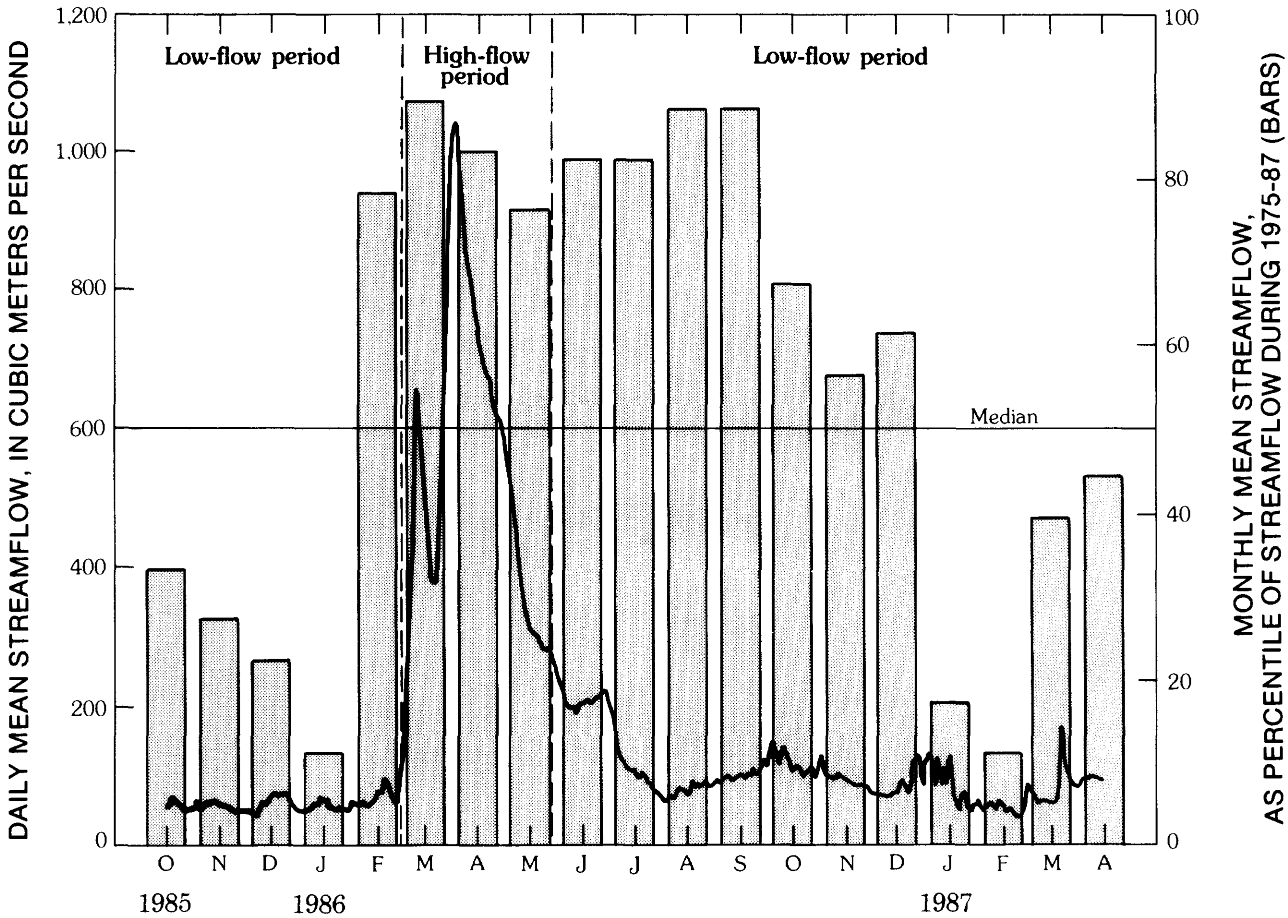

FIGURE 2. Daily mean streamflow at site 11, near Vernalis, compared to monthly mean streamflow as percentile of flows for the same month during 1975-87.

mid-February and March 1986, the recession of the flood waters took several months. This prolonged recession resulted in greater than normal flows during mid-May 1986 through December 1987 partly because of continuing release of water from reservoirs in the Sierra Nevada. From January to April 1987, monthly mean streamflows were less than the 50th percentile of monthly mean streamflows during 1975-87. Daily mean streamflows at Vernalis were summed for the entire 18-month study period to determine the quantity of water contributed by the San Joaquin River to the Sacramento-San Joaquin River Delta. Of a total of $7.8 \cdot 10^9$ m^3 of streamflow during the study period, 49 percent occurred during the 15-month combined low-flow period and 51 percent during the 3-month high-flow period (table 2).

TABLE 2.--*Summary of streamflow*

[m^3/s, cubic meter per second; m^3, cubic meter]

Streamflow at study sites

Site No.	Low-flow period (468 days): Total streamflow (percentage of site 11)	Low-flow: Streamflow (m^3/s) 25th percentile	Low-flow: Median	Low-flow: 75th percentile	High-flow period (79 days): Total streamflow (percentage of site 11)	High-flow: Streamflow (m^3/s) 25th percentile	High-flow: Median	High-flow: 75th percentile
1	6	1.7	2.9	5.8	41	140	260	350
2	7	4.0	6.0	8.6	2	9.6	11	12
3	14	6.7	9.2	16	42	140	250	330
4	2	.83	1.7	3.3	1	4.1	6.8	9.9
5	11	6.4	6.9	9.1	12	63	71	96
6	28	15	21	29	56	180	330	440
7	37	21	29	39	58	200	340	450
8	30	13	19	34	26	130	160	180
9	75	46	57	76	90	350	530	670
10	24	15	20	33	15	43	75	120
11	100	61	81	106	100	400	560	720

Low-flow period: Total streamflow at site 11: $3.8 \cdot 10^9$ m^3

High-flow period: Total streamflow at site 11: $4.0 \cdot 10^9$ m^3

Within-reach changes in streamflow

River reach (downstream site No.)	Low-flow period (21 measurements): Gain or loss (percentage of site 11) 25th percentile	Low-flow: Median	Low-flow: 75th percentile	High-flow period (6 measurements): Gain or loss (percentage of site 11) 25th percentile	High-flow: Median	High-flow: 75th percentile
3	0.3	0.8	1.5	-3.1	0.1	1.6
6	.3	1.3	2.3	.5	.7	1.5
7	6.8	8.9	12	2.5	4.8	8.8
9	5.3	9.8	13	3.0	8.0	10
11	-2.2	2.6	4.3	-7.6	-5.6	-2.5

Low Flow

During the combined low-flow period, the sum of total streamflows of the five major tributaries to the lower San Joaquin River (sites 2, 4, 5, 8, and 10) and the upper San Joaquin River (site 1) accounted for 80 percent of the total streamflow at Vernalis, where the median streamflow was 81 m^3/s (table 2). The eastside tributaries alone (sites 5, 8, and 10) contributed 65 percent of the total streamflow at Vernalis. The San Joaquin River near Stevinson (site 1) contributed 6 percent of the Vernalis streamflow, and Salt and Mud Sloughs (sites 2 and 4) only 9 percent. The median streamflow in Salt Slough was more than three times that in Mud Slough. Total streamflows indicate that about 20 percent of the flow measured at Vernalis was from unmeasured sources between sites.

Within-reach (between-site) changes in streamflow during the low-flow period were determined between each San Joaquin River site (3, 6, 7, 9, and 11) and its upstream tributaries for each of the 21 water-chemistry sampling events. The analysis was limited to these 21 measurements during low-flow conditions so that direct comparisons could be made with similar analyses of dissolved-solids and selenium loads, which are based on the chemical analyses.

If all streamflows into a reach are accounted for at monitoring sites, then the sum of measured streamflows at upstream tributary sites (for instance, sites 1 and 2) should equal streamflow at the downstream end of that reach (site 3), after adjusting for traveltime within the reach. A gain within the reach indicates addition of water from unmeasured sources; a loss within the reach indicates seepage losses or withdrawals. In table 2 and in subsequent similar compilations for dissolved solids and selenium, within-reach changes are expressed as a percentage of streamflow or load at Vernalis in order to emphasize their relative importance.

The median value and the 25th and 75th percentiles were determined from estimates of the within-reach gain (or loss) of streamflow for each water-chemistry sampling date. The Wilcoxon signed ranks test was used to determine whether the median within-reach changes were significantly different from zero. Within-reach gains in streamflow were significant (α=0.05) for all reaches except the one ending at site 11. The greatest gains occurred in reaches between sites 6 and 7, between upstream sites 7 and 8, and site 9 downstream. Those within-reach gains represented a combined total of about 19 percent of the streamflow at Vernalis. This agrees well with the estimate from total streamflows that about 20 percent of Vernalis streamflow was not measured at study sites on tributaries.

Within-reach gains in streamflows during low-flow conditions were more closely examined in a streamflow accounting study during October 28-29, 1986. Every discharge to and withdrawal from the San Joaquin River was monitored in the reach between sites 6 and 7. This reach was selected for study because there are no major tributaries, but preliminary data analysis indicated that within-reach gains in streamflow are substantial. During the 2-day study, the within-reach gain in streamflow was 7.8 m^3/s. Of this gain, 73 percent was from measured surface-water inflows. The remaining 27 percent of the total gain was estimated to be ground-water inflow to the reach between sites 6 and 7. The estimated ground-water inflow within the reach represented about 2 percent of streamflow at Vernalis.

The quantity of unmeasured flow that enters the San Joaquin River varied seasonally during the low-flow period. For example, the median difference in daily mean streamflow between sites 6 and 7, which approximates within-reach gains for this reach, was 6.6 m3/s between October 1985 and mid-February 1986; 11 m^3/s between mid-May 1986 and October 1986; and 4.8 m^3/s between November 1986 and March 1987. The greatest within-reach gains occurred during the summer in 1986 when irrigation was heavy.

High Flow

During the high-flow period, the sum of estimated total streamflows of the five main tributaries to the lower San Joaquin River (sites 2, 4, 5, 8 and 10) and the upper San Joaquin River (site 1) accounted for 97 percent of total streamflow at Vernalis, where the median streamflow was 560 m^3/s (table 2). The eastside tributaries represented 53 percent of the Vernalis streamflow, slightly less than they did during low flow, but the total streamflow of the upper San Joaquin River at site 1 was 41 percent of the streamflow at Vernalis, compared to only 6 percent during low flow. The source of water upstream of site 1 during the high-flow period was mainly San Joaquin River water released from Friant Dam. Salt and Mud Sloughs represented only 3 percent of the streamflow at Vernalis, about one-third their proportional contribution of streamflow to Vernalis during the low-flow period.

Median within-reach gains in streamflow were greatest upstream of sites 7 and 9 (4.8 and 8.0 percent of streamflow). Though a within-reach loss of water is indicated between site 11 and sites 9 and 10, this is probably attributable to measurement problems during high-flow conditions. Generally, between-site differences during high-flow conditions are more difficult to interpret and represent a smaller component of total flow than during low-flow conditions.

SOURCES AND TRANSPORT OF DISSOLVED SOLIDS AND SELENIUM

Future decisions on management of tile-drain water in the western San Joaquin Valley and its effects on the water quality of the San Joaquin River depend partly on attaining a quantitative understanding of the sources and transport of dissolved solids and selenium in the river. The sources and transport of dissolved solids and selenium depend on concentration and streamflow, which determine load. High streamflow combined with low concentrations may make a substantial contribution to loading into a river. However, high concentrations combined with low streamflow also may contribute to high loads. Dissolved contaminants, such as selenium, often have the greatest effect on water quality during low flows.

Dissolved Solids

Dissolved-solids loads were calculated for each site for low- and high-flow periods using regression relations of the general form:

$$\ln DSL = a_1 \cdot \ln Q + a_2 \cdot \ln SC + a_3 \qquad (3)$$

where

DSL is dissolved-solids load, in kilograms per day,

Q is daily mean streamflow, in cubic meters per second,

SC is daily mean specific conductance, in microsiemens per centimeter, and

a_1, a_2, a_3 are coefficients of the regression equation.

The regression relations for the high-flow period were developed from all available measurements, and for the low-flow period they were developed from measurements only during the low-flow period.

Values of *DSL* were computed from regression estimates of ln*DSL* by:

$$DSL = e^{\ln DSL} \cdot \sum_{n}^{i=1} \frac{e^{res_i}}{n} \qquad (4)$$

where res_i is the residual between the regression relation and the actual value for each of the measurements, *n*. The second term in equation 4 is necessary in order to correct the bias inherent in untransforming the logarithmic regression estimate, ln*DSL*.

Two regression relations were derived for each site and flow period: one that uses both *Q* and *SC* to estimate *DSL* and one that uses only *Q*. The second relation was used only when daily data were not available for specific conductance. This occurred for substantial periods of time at some sites during the 547-day study period: 547 days at site 6, where data from the continuous monitor did not adequately represent the cross section; 324 days at site 8; 210 days at site 1; 147 days at site 9; and 40 to 100 days at sites 2, 3, 4, 5, and 11. Standard deviations of regression relations for estimating ln*DSL* for the low-flow period ranged from 0.07 to 0.13 for the two-variable equations and from 0.13 to 0.43 for the one-variable equation.

The dissolved-solids load from the San Joaquin River at Vernalis to the delta for the entire 18-month period (fig. 3) was estimated using daily mean streamflow and specific conductance. Of the total load of $1.7 \cdot 10^9$ kg, 76 percent occurred during the low-flow period and 24 percent during the high-flow period (table 3).

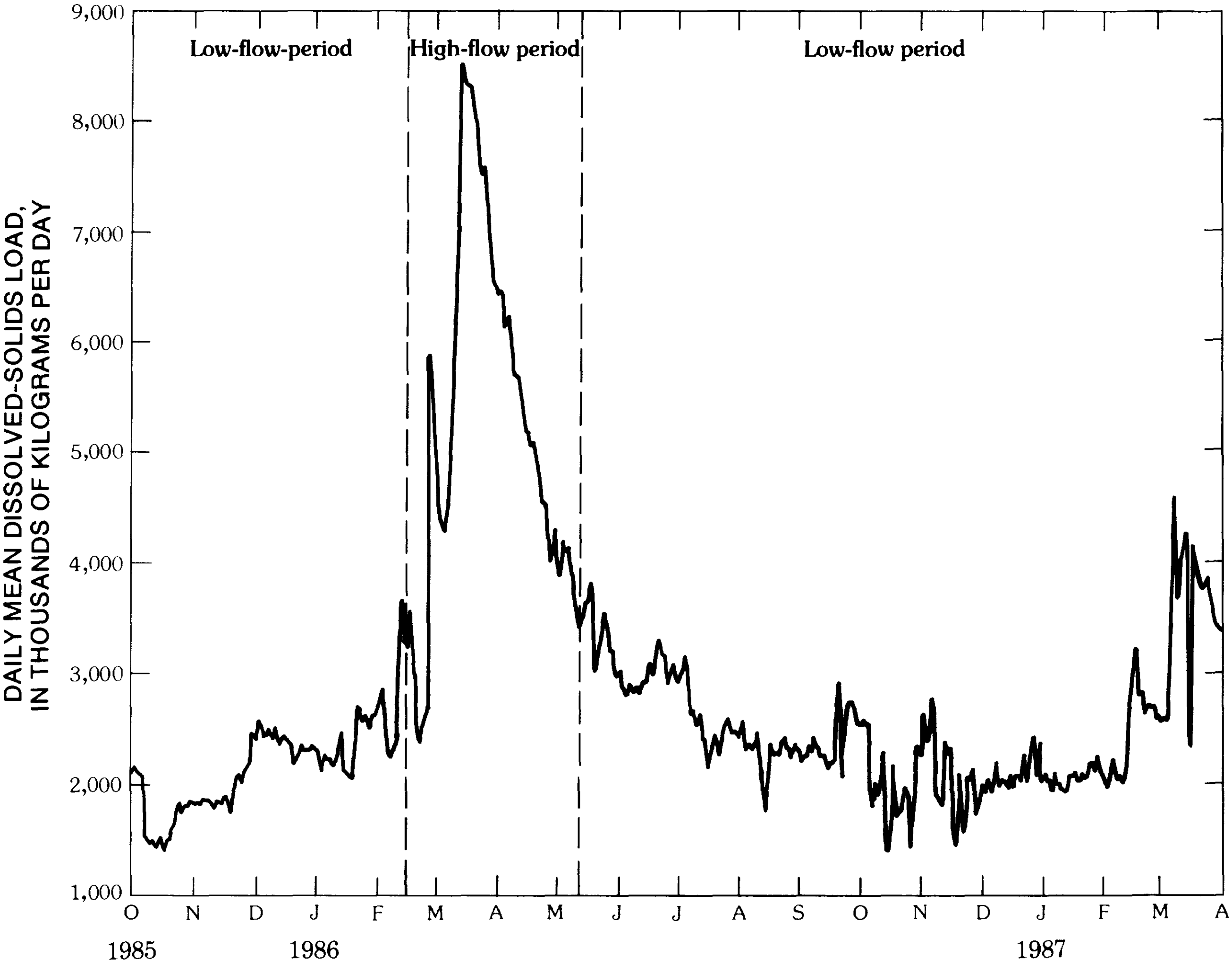

FIGURE 3. Estimated dissolved-solids loads for the San Joaquin River at site 11.

Low Flow

Total loading of dissolved solids estimated for each site during low flow (table 3), expressed as a percentage of the site 11 load, is shown in figure 4 along with streamflow and selenium load. During the low-flow period, the sum of total loads of the five major tributaries to the lower river (sites 2, 4, 5, 8, and 10) and the upper San Joaquin River (site 1) accounted for 58 percent of the total load at Vernalis (site 11). Median dissolved-solids loads ranged

TABLE 3.--*Summary of dissolved-solids loads*

[kg, kilogram; kg/d, kilogram per day]

Dissolved-solids loads at study sites

Site No.	Low-flow period (468 days): Total load (percentage of site 11)	Low-flow Load (10^3 kg/d): 25th percentile	Median	75th percentile	High-flow period (79 days): Total load (percentage of site 11)	High-flow Load (10^3 kg/d): 25th percentile	Median	75th percentile
1	4	46	77	120	25	660	1,100	2,000
2	26	380	540	680	20	910	980	1,200
3	30	550	720	850	31	1,200	1,600	2,100
4	14	130	280	530	15	580	860	1,100
5	3	65	74	87	5	230	260	340
6	55	1,100	1,200	1,500	82	3,500	4,600	5,200
7	68	1,200	1,600	2,000	85	3,500	4,600	5,800
8	7	120	140	210	10	460	560	560
9	89	1,900	2,100	2,300	100	4,400	5,300	6,000
10	4	64	85	110	7	200	320	530
11	100	2,050	2,300	2,700	100	4,300	5,400	6,500

Total load at site 11: $1.3 \cdot 10^9$ kg | Total load at site 11: $0.4 \cdot 10^9$ kg

Within-reach changes in dissolved-solids loads

River reach (downstream site No.)	Low-flow period (21 measurements) Gain or loss (percentage of site 11): 25th percentile	Median	75th percentile	High-flow period (6 measurements) Gain or loss (percentage of site 11): 25th percentile	Median	75th percentile
3	1.3	3.9	8.5	-17	-11	6.0
6	-1.2	5.5	11	-15	13	41
7	12	18	23	-10	14	19
9	8.4	15	24	11	17	20
11	-2.7	1.4	7.7	-10	-4.3	5.3

from $74 \cdot 10^3$ to $140 \cdot 10^3$ kg/d in eastside tributaries (sites 5, 8 and 10) and in the San Joaquin River at site 1. The combined total load at these four sites was only 18 percent of the total low-flow load in the San Joaquin River at site 11 even though their contribution of total streamflow was 71 percent. Median dissolved-solids loads in Salt and Mud Sloughs were $540 \cdot 10^3$ and $280 \cdot 10^3$ kg/d and their combined total load was 40 percent of the total load at site 11, whereas their contribution to streamflow was only 9 percent. Median dissolved-solids loads in the San Joaquin River increased downstream from $77 \cdot 10^3$ kg/d at site 1 to $2,300 \cdot 10^3$ kg/d at site 11.

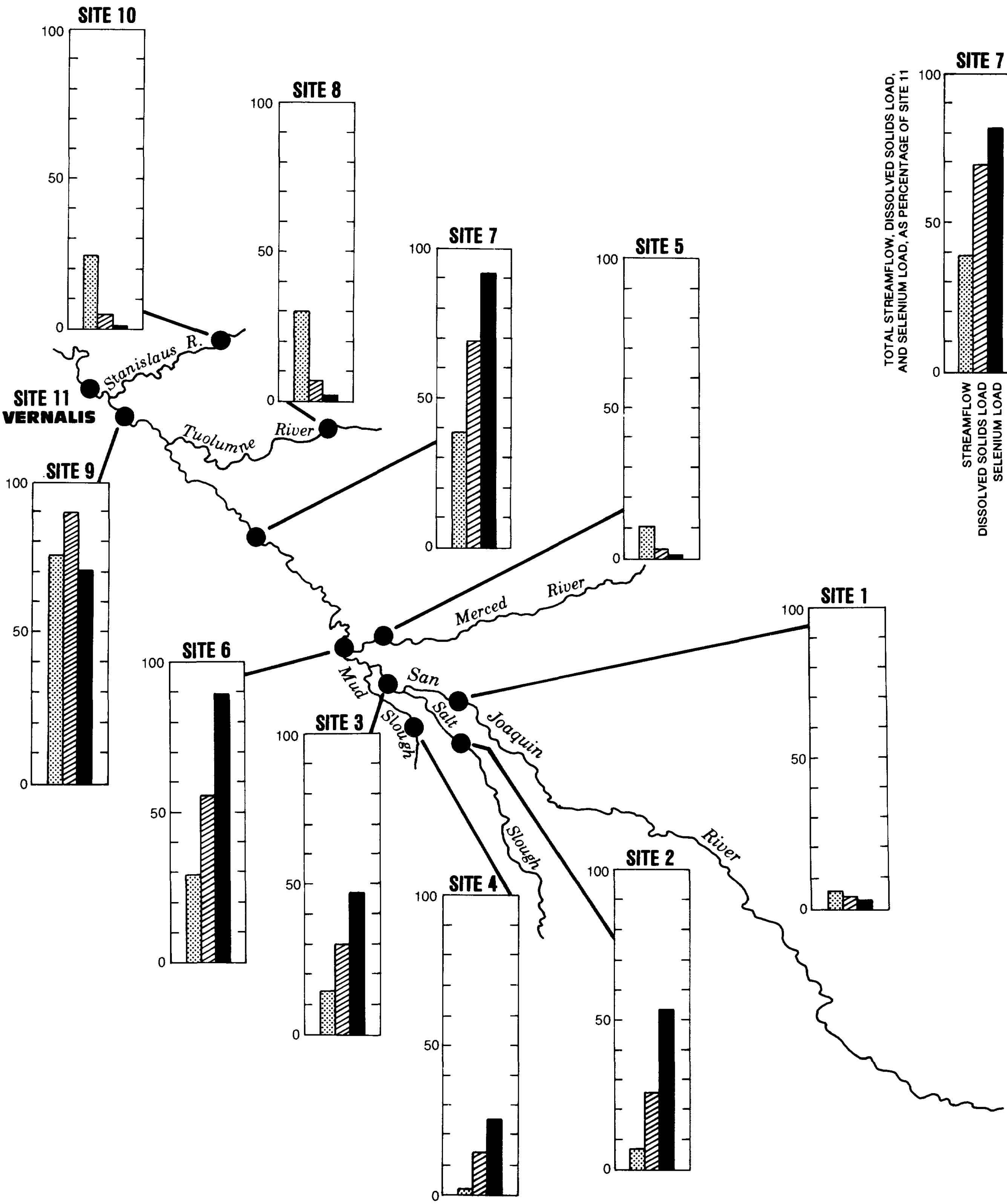

FIGURE 4. Streamflow, dissolved-solids loads, and selenium loads in the San Joaquin River and its tributaries during the low-flow period.

The total load of dissolved solids from major tributaries to the lower river accounted for only 58 percent of the total load estimated for site 11, which indicates that unmeasured, within-reach sources may account for 42 percent or almost one-half the dissolved solids transported past site 11. This compares to the similarly derived estimate of 20 percent for the quantity of streamflow from unmeasured sources, implying that the average concentration of dissolved solids in unmeasured inflows is more than twice the average concentration of all tributary inflows measured in this study. Estimates indicate that most of the unmeasured load occurs in the reaches of river between sites 6 and 9 (table 3, fig. 4).

Within-reach changes in dissolved-solids loads were more closely examined using the mass balances computed for each of the 21 water-chemistry sampling events during the low-flow period (table 3). The greatest within-reach gains in dissolved-solids load in the river were between sites 6 and 7, and between sites 7 and 9. In those two reaches combined, a median of 33 percent of the site 11 load entered the river from unmeasured sources of surface and ground water. This conclusion is supported by results of the Wilcoxon test, which indicates that within-reach gains in dissolved-solids loads were significant ($\alpha=0.05$) in reaches upstream of sites 3, 6, 7, and 9. The same sites showed significant within-reach gains in streamflow.

High Flow

Median dissolved-solids loads were higher at all the sites during the high-flow period, despite generally lower concentrations, because of increased streamflows at all sites (table 3). The relative contribution to the site 11 load from eastside tributaries (22 percent) and the upper San Joaquin River at site 1 (25 percent) increased to 47 percent compared to 18 percent for the low-flow period, and the contribution from Salt and Mud Sloughs was proportionally less at 35 percent. Median loads increased downstream in the San Joaquin River from $1,100 \cdot 10^3$ kg/d at site 1 to $5,400 \cdot 10^3$ kg/d at Vernalis (site 11).

During the high-flow period, the total load of dissolved solids from the major tributaries to the lower river (sites 2, 4, 5, 8 and 10) and the upper river (site 1) accounted for 82 percent of the site 11 total load, compared to only 58 percent during the low-flow period. Thus, the relative contribution of unmeasured sources was much less. However, there must have been unmeasured inflows of water with relatively high dissolved-solids concentrations during the high-flow period because streamflow from the main tributaries accounted for 97 percent of the site 11 flow. The total-load data indicate that the greatest gains in load from unmeasured inflows were between sites 3 and 6.

Because within-reach changes in load are relatively less important during the high-flow period, they are more difficult to assess. In addition, directly measured loads are available for only six points in time during the high-flow conditions. Nevertheless, significant ($\alpha=0.05$) within-reach gains in load were evident from the six mass-balance estimates in reaches upstream from sites 6, 7, and 9 (table 3).

Selenium

Selenium loads were calculated for all but one site for low- and high-flow periods using regression relations of the general form:

$$\ln SeL = a_1 \cdot \ln Q + a_2 \cdot \ln SC + a_3 \qquad (5)$$

where *SeL* is selenium load, in kilograms per day, and all other terms are the same as in equation 3. Values of *SeL* were computed from regression estimates of ln*SeL* by equation 4, with *SeL* replacing *DSL*. For site 2, log-transformation was not required for any of the variables.

As for dissolved solids, there are two regression relations for each site and flow period; one that uses both *Q* and *SC* and a second that includes only *Q*. The second relation was used for the days for which no specific-conductance data were available. Standard deviations of regression relations for estimating ln*SeL* ranged from 0.34 to 1.4 for the two-variable equations and from 0.59 to 1.5 for the one-variable equations. Excluding site 1 where loads were always extremely low, standard deviations for the one-variable equations ranged from 0.59 to 1.2.

The dissolved-selenium load from the San Joaquin River at site 11 to the delta for the entire 18-month period (fig. 5) was estimated using the regression relations developed. Of the total load of $6.5 \cdot 10^3$ kg, 65 percent occurred during the low-flow period and 35 percent during the high-flow period (table 4).

Low Flow

Total selenium loading was estimated for each site during low flow (table 4), expressed as a percentage of the site 11 load (see fig. 4), and compared to streamflow and dissolved-solids loads. During the low-flow period, the sum of total loads of the five major tributaries to the lower river (sites 2, 4, 5, 8, and 10) and the upper San Joaquin River (site 1) accounted for 85 percent of the total load at Vernalis (site 11). Together, the eastside tributaries (sites 5, 8, and 10) and the upper San Joaquin River (site 1) accounted for only 7 percent of the Vernalis load and had median loads ranging from 0.08 to 0.14 kg/d. Salt and Mud Sloughs contributed 78 percent of the total Vernalis load, with median loads of 4.7 and 0.94 kg/d, respectively (table 4; fig. 5).

The estimates indicate that the main tributaries to the lower river contributed most of the selenium load estimated for Vernalis. They also show that most selenium that reaches Vernalis comes from Salt and Mud Sloughs and that within-reach gains of selenium are absent or relatively small. This contrasts with dissolved solids (fig. 4) for which Salt and Mud Sloughs accounted for only 40 percent of the low-flow load at Vernalis and within-reach gains were a major source.

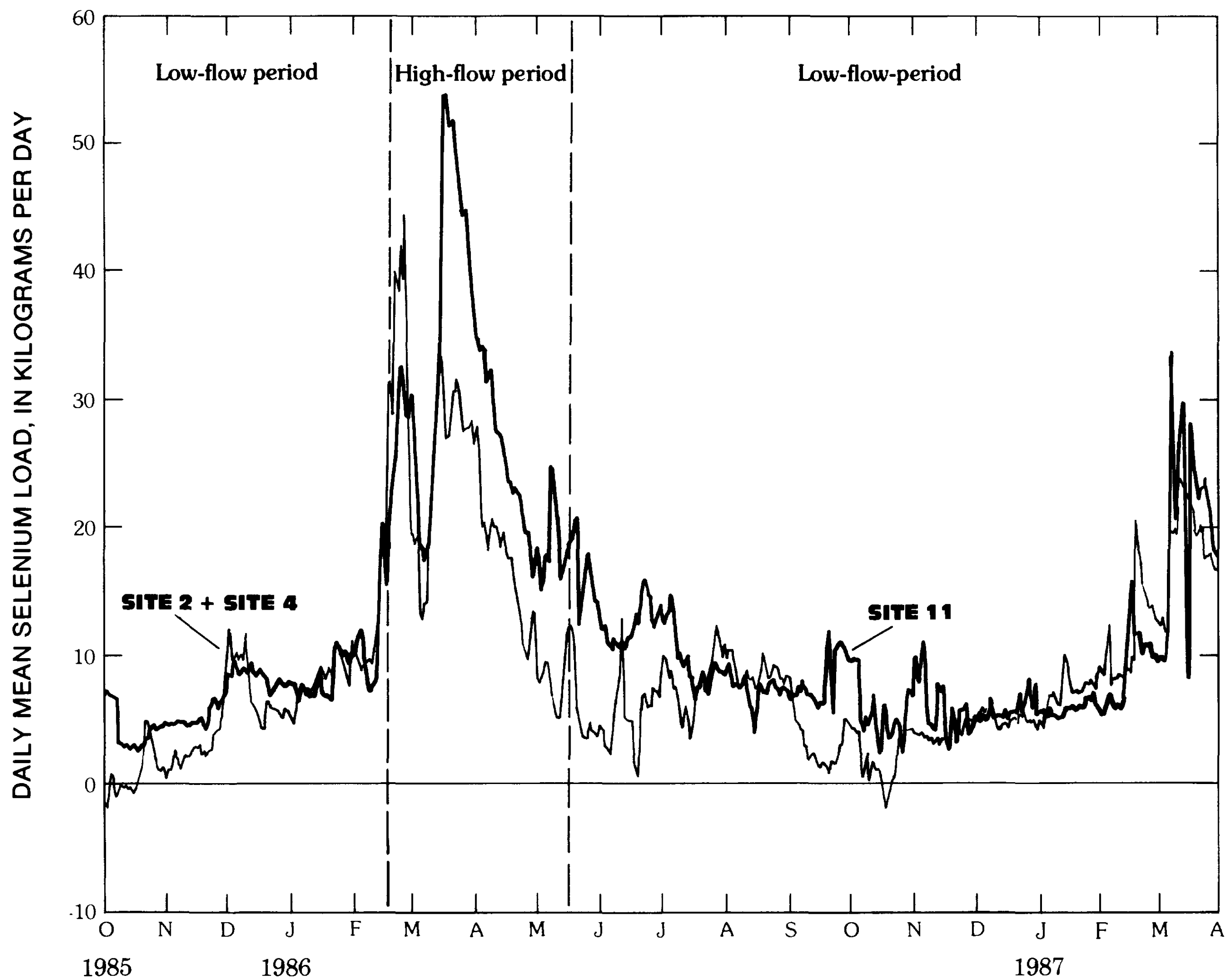

FIGURE 5. Estimated selenium loads for the San Joaquin River at site 11 and for Salt and Mud Sloughs combined (sites 2 and 4).

Within-reach changes in selenium loads were more closely examined using the mass balances computed for each of the 21 water-chemistry sampling events during the low-flow period (table 4). Estimates of within-reach changes were highly variable probably because of the low concentration and analytical variance associated with selenium. Though median values indicate increased selenium load in all reaches, none of the gains were significantly (α=0.05) greater than zero when combined for the entire low-flow period. The results of the mass-balance analysis indicate that substantial within-reach net losses, which were one explanation for discrepancies in total-load estimates, probably did not occur. In reality, there likely were small within-reach gains in selenium load that occurred because of the within-reach gains in streamflow,

TABLE 4.--*Summary of selenium loads*

[kg, kilogram; kg/d, kilogram per day]

Dissolved-selenium loads at study sites								
	Low-flow period (468 days)				High-flow period (79 days)			
Site No.	Total load (percentage of site 11)	Load (kg/d) 25th percentile	Load (kg/d) Median	Load (kg/d) 75th percentile	Total load (percentage of site 11)	Load (kg/d) 25th percentile	Load (kg/d) Median	Load (kg/d) 75th percentile
1	3	0.06	0.13	0.29	18	3.6	6.5	8.5
2	53	2.2	4.7	6.4	32	7.6	9.1	15
3	47	2.2	3.9	5.0	13	2.0	4.2	6.0
4	25	.09	.94	4.0	51	5.1	10	14
5	1	.08	.08	.09	2	.40	.71	1.2
6	89	4.8	6.4	8.7	77	20	27	31
7	92	3.3	6.5	10	57	12	17	26
8	2	.10	.14	.20	4	1.1	1.5	1.7
9	71	3.9	5.9	7.5	74	17	23	30
10	1	.07	.10	.15	3	.42	.81	1.4
11	100	5.8	7.6	10	100	20	27	34
	Total load at site 11: $4.2 \cdot 10^3$ kg				Total load at site 11: $2.3 \cdot 10^3$ kg			

Within-reach changes in selenium loads						
	Low-flow period (21 measurements)			High-flow period (6 measurements)		
	Gain or loss (percentage of site 11)			Gain or loss (percentage of site 11)		
River reach (downstream site No.)	25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
3	-3.2	1.6	19	-53	-33	6.6
6	-4.4	3.5	15	-5.8	17	53
7	-5.3	4.8	18	-26	-9.4	12
9	-25	9.4	18	-20	2.3	60
11	-16	2.0	18	5.7	12	42

small within-reach losses of selenium load to bed sediments, and biological uptake. Selenium concentrations in bed sediments of Salt and Mud Sloughs are higher than at other study sites and higher than concentrations in surrounding soils (Clifton and Gilliom, 1989), indicating losses of selenium from the water column to the bed sediments where selenium concentrations in the water were highest.

High Flow

During the high-flow period, median selenium loads were higher at all sites (table 4). Even though the high-flow period was only about 17 percent as long as the low-flow period, it accounted for about 35 percent of the total selenium load at Vernalis during the study period. Compared to the low-flow period, the contribution to the total Vernalis load from the upper San Joaquin River at site 1 was much greater (18 percent). The relative contribution of Salt and Mud Sloughs (83 percent) was only slightly more than during low flow, but Mud Slough was the dominant source. Median loads in the San Joaquin River increased downstream during the high-flow period from 6.5 kg/d at site 1 to 27 kg/d at site 11.

Beyond these general patterns, detailed interpretation of loads during the high-flow period, particularly of within-reach changes, is not warranted. The uncertainty in the total-load estimates is high and some of the total-load estimates do not make reasonable sense. For example, the site 1 load (18 percent) plus the site 2 load (32 percent) should be close to the site 3 load (13 percent). During high-flow conditions, within-reach changes were expected to be small relative to the major additions of water at sites 1, 5, 8, and 10. In fact, within-reach changes computed from the mass-balance analysis for the six selenium measurements during the high-flow period were highly variable but were not significantly ($\alpha=0.05$) different from zero for all reaches.

CONCENTRATIONS OF DISSOLVED SOLIDS AND SELENIUM

Concentrations of dissolved solids and selenium in the San Joaquin River reflect their individual sources and the effects of dilution. Subsurface agricultural drain water with high selenium concentrations tends to have high concentrations of dissolved solids (Deverel and others, 1984). However, high dissolved-solids concentrations also may occur in water with low selenium concentrations, such as subsurface drain water from low-selenium areas, some agricultural surface runoff, or ground water (Neil, 1986; Chilcott and others, 1988). The occurrence of both general types of source waters in the San Joaquin River drainage basin complicates the association between selenium and dissolved-solids concentrations.

Dissolved Solids

Dissolved-solids concentrations are summarized in table 5. During the low-flow period, median dissolved-solids concentrations were highest in Salt Slough (1,070 mg/L) and Mud Slough (1,810 mg/L), and lowest in the three eastside tributaries (69 to 110 mg/L). Concentrations in the San Joaquin River increased downstream between sites 1 and 3 from 286 to 869 mg/L because of high-concentration inflow from Salt Slough. Median concentrations decreased downstream in the river between sites 3 and 11 from 869 to 347 mg/L because of dilution by streamflow from eastside tributaries.

TABLE 5.--*Summary of dissolved-solids concentrations*

	Dissolved-solids concentrations, in milligrams per liter					
	Low-flow period (21 samples)			High-flow period (6 samples)		
Site No.	25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
1	176	286	434	54	70	88
2	732	1,070	1,730	840	1,153	1,670
3	610	869	1,275	62	85	202
4	1,480	1,810	2,265	813	1,480	3,000
5	95	110	124	38	51	69
6	402	668	962	137	168	220
7	440	658	905	133	180	227
8	66	94	106	30	40	50
9	308	466	634	116	140	168
10	58	69	86	46	50	58
11	256	347	462	103	121	170

During the high-flow period, dilution effects of precipitation and surface-water runoff resulted in lower median dissolved-solids concentrations than during the low-flow period at all sites except Salt Slough. The highest dissolved-solids concentrations were in Salt and Mud Sloughs, and the lowest concentrations were in the eastside tributaries. Concentrations generally decreased downstream in the San Joaquin River because of dilution by eastside tributaries, except between sites 6 and 7 where no major tributaries enter.

The California State Water Resources Control Board has set specific water-quality standards to protect water quality in the delta; the standard for the San Joaquin River at Vernalis is 500 mg/L. The recommended criterion for the remainder of the river (upstream of Vernalis) is 1,000 µS/cm for specific conductance, which is equivalent to about 650 to 700 mg/L of dissolved solids (California State Water Resources Control Board, 1987). Of the 37 measurements of dissolved solids at Vernalis (site 11) during the study period, 11 percent (four samples) were greater than 500 mg/L, and concentrations that exceeded 500 mg/L ranged from 501 to 547 mg/L. Concentrations during the low-flow period exceeded the recommended criterion of about 650 mg/L more than one-half the time at sites 2, 3, 4, 6, and 7 and more than 75 percent of the time at sites 2, 3, and 4. During the high-flow period, 650 mg/L was regularly exceeded only in Salt and Mud Sloughs (sites 2 and 4), where more than 800 mg/L was measured in 75 percent of the samples.

Specific conductance and dissolved solids are closely related and are highly correlated in the San Joaquin River and tributaries. Values of r^2 for regression relations between the logarithms of specific conductance and dissolved solids were greater than 0.90 at all sites except the Stanislaus River, for which r^2 was 0.80 (α=0.05). Daily mean specific conductances in the San Joaquin River at site 11, near Vernalis (fig. 6), illustrate the general differences in dissolved solids during low and high flows and the variability of concentrations during the different flow periods.

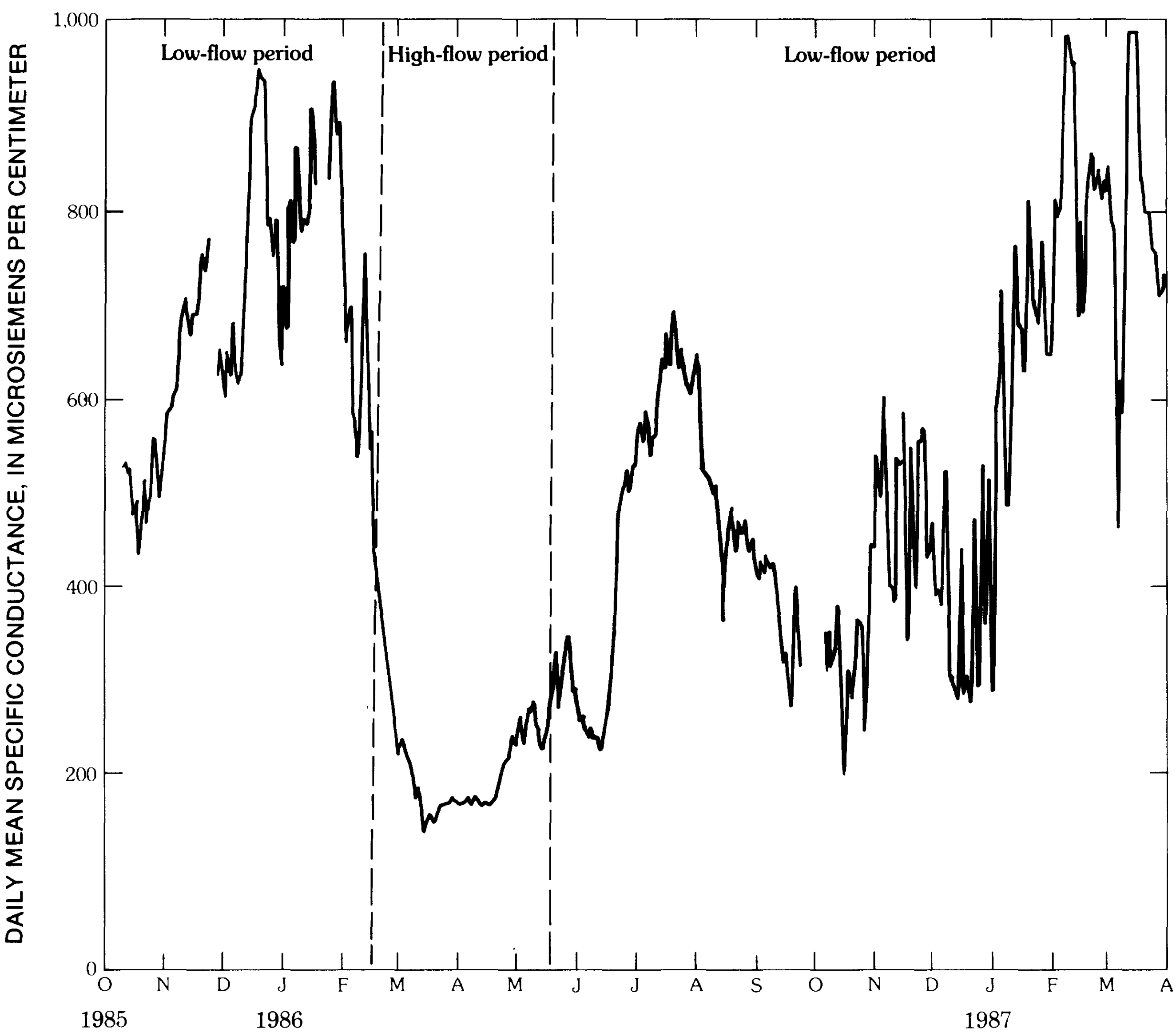

FIGURE 6. Daily mean specific conductance for the San Joaquin River at site 11.

Selenium

Selenium concentrations are summarized in table 6. During the low-flow period, median selenium concentrations were highest in Salt Slough (5.5 μg/L) and Mud Slough (8.8 μg/L). Both sloughs receive inflow of subsurface agricultural drain water, much of which is high in selenium. In Mud Slough, the maximum concentration measured was 28 μg/L on July 15, 1986, and the maximum concentration measured in Salt Slough was 22 μg/L on January 21, 1987. Concentrations were lowest in the three eastside tributaries (≦0.1 μg/L). The median

TABLE 6.--*Summary of selenium concentrations*

[µg/L, microgram per Liter; <, value is less than actual value shown]

	Selenium concentrations (µg/L)					
	Low-flow period (21 samples)			High-flow period (6 samples)		
Site No.	25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
1	0.1	0.3	0.6	<0.1	0.2	0.3
2	2.1	5.5	14	7.4	13	18
3	1.4	5.2	8.1	.1	.2	1.2
4	3.0	8.8	21	2.2	3.9	18
5	<.1	.1	.2	<.1	.2	.2
6	1.6	2.7	5.4	.4	1.1	1.3
7	1.3	2.3	4.2	.3	.8	1.3
8	<.1	<.1	.1	<.1	.1	.2
9	.6	1.1	2.0	.4	.7	.8
10	<.1	<.1	.2	<.1	.1	.2
11	.6	1.0	1.4	.5	.7	.9

selenium concentration in the San Joaquin River at site 1, upstream of Salt and Mud Sloughs, was 0.3 µg/L. Median selenium concentrations in the San Joaquin River decreased from 5.2 µg/L at site 3 to 1.0 µg/L at site 11, near Vernalis, as the low-selenium water from the eastside tributaries and unmeasured sources entered the river.

During the high-flow period, as with dissolved solids, selenium concentrations were generally lower than during the low-flow period because of greater dilution by Sierra Nevada runoff. In Salt Slough, however, selenium concentrations were greater during the high-flow period. Median selenium concentrations were highest in Salt Slough (13 µg/L) and Mud Slough (3.9 µg/L). The maximum concentration measured in Salt Slough was 20 µg/L on February 26, 1987, and the maximum concentration measured in Mud Slough was 24 µg/L on April 16, 1986. Concentrations were lowest in eastside tributaries and in the San Joaquin River at site 1 (0.1 to 0.2 µg/L). Median selenium concentrations decreased downstream in the San Joaquin River between sites 6 and 11 from 1.1 to 0.7 µg/L because of dilution by eastside tributaries.

Selenium concentrations in the San Joaquin River at Vernalis during October 1985 to March 1987 ranged from 0.3 to 2.8 µg/L (fig. 7). During this period, concentrations were low in October and November and steadily increased until February, generally corresponding to an increased quantity of subsurface drain water discharged to the river (Kratzer and others, 1987; California State Water Resources Control Board, 1987). Concentrations in Salt and Mud Sloughs were more variable (fig. 7). Concentrations in Salt Slough were higher in winter, and in Mud Slough they were higher in summer. The variability is related to the management of the subsurface agricultural drain water, to the source of high-selenium water to these sloughs, and to irrigation-return flows and releases of Delta-Mendota Canal water, which dilute the drain water prior to downstream discharge.

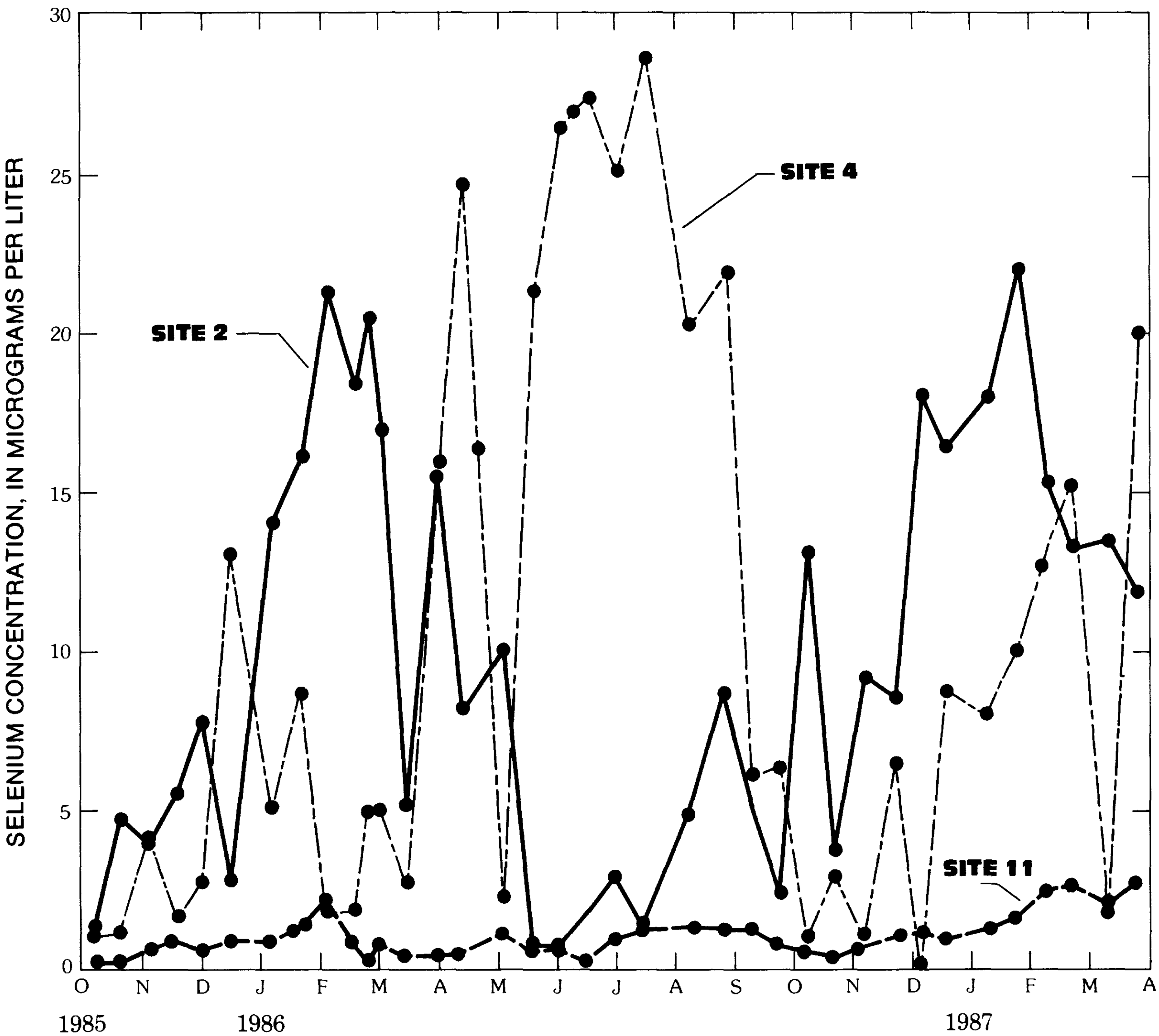

FIGURE 7. Measured selenium concentrations for the San Joaquin River at site 11 and for Salt Slough (site 2) and Mud Slough (site 4).

Significance to Water Quality

The most likely form of selenium toxicity to fish and wildlife is through bioaccumulation. There are large ranges of measured acute toxicity concentrations of selenium in aquatic test organisms (U.S. Environmental Protection Agency, 1987). Presently estimated continuous, long-term selenium criteria for protection of aquatic life in the San Joaquin River basin are 1.0 µg/L in impounded water (such as lakes and marshes) and 2.6 µg/L in flowing water; and the criterion for maximum instantaneous concentration in flowing water is 26 µg/L (California State Water Resources Control Board, 1987). Because of insufficient bioaccumulation data for the San Joaquin River, the State of California has proposed an interim objective of a maximum mean monthly selenium concentration of 5 µg/L in the San Joaquin River at site 6 (California State Water Resources Control Board, 1987). The State has recommended long-term objectives of 2 µg/L of selenium at site 6 to protect waters of the San Joaquin River that are impounded for wetland habitat and 10 µg/L of selenium for Salt and Mud Sloughs. The present Federal standard for selenium in drinking water is 10 µg/L (U.S. Environmental Protection Agency, 1986). The Federal criterion for protection of freshwater aquatic organisms is a 4-day average of 5 µg/L no more than once every 3 years on the average, and the 1-hour average concentration should not exceed 20 µg/L more than once every 3 years on the average (U.S. Environmental Protection Agency, 1987).

Cumulative frequency distributions of dissolved-selenium concentrations for sites 2, 3, 4, 6, 7, 9, and 11 can be used to estimate the proportion of time that a criterion was exceeded (fig. 8). Thirty-seven measurements were used for sites 2, 4, 11, and 27 measurements at the remaining sites. Cumulative frequencies for the eastside tributaries and the San Joaquin River at Stevinson (site 1) are not shown because selenium concentrations did not exceed 2 µg/L.

Sites 5 and 6 are only 0.32 km apart, and there are no other inflows to the river at this point. A mass-balance computation based on data for these sites can be used to estimate selenium concentrations and loads in the San Joaquin River just upstream of site 6. Selenium concentrations at that location were determined by the difference in selenium loads, divided by the difference in streamflows, between sites 5 and 6. Results for this location represent the effects of Salt and Mud Sloughs, the upper San Joaquin River, and other ungaged sources on selenium concentrations in the river prior to dilution by the Merced River (fig. 8). Samples collected by the Central Valley Regional Water Quality Control Board from the San Joaquin River immediately upstream of the Merced River inflow support these computed estimates of selenium concentrations (James and others, 1988). Twenty-four grab samples were collected from October 1985 to March 1987, and total recoverable selenium concentrations were 2, 4.6, and 7 µg/L for the 25, 50, and 75th percentiles, respectively. These values for the percentiles are similar to the same percentiles derived from estimates from this study of selenium concentrations just upstream of site 6. The estimated concentrations from this study indicate 25, 50, and 75th percentiles of about 2, 4, and 8 µg/L, respectively.

The cumulative frequency distributions show that the drinking-water standard (10 µg/L) was exceeded in the San Joaquin River downstream of Salt and Mud Sloughs at site 3 and just upstream of site 6 about 10 percent of the time. The drinking-water standard was exceeded in the sloughs about 40 percent of the time. The proposed 4-day average aquatic-life criterion of 5 µg/L was exceeded in more than 60 percent of the samples from the sloughs and in samples from the

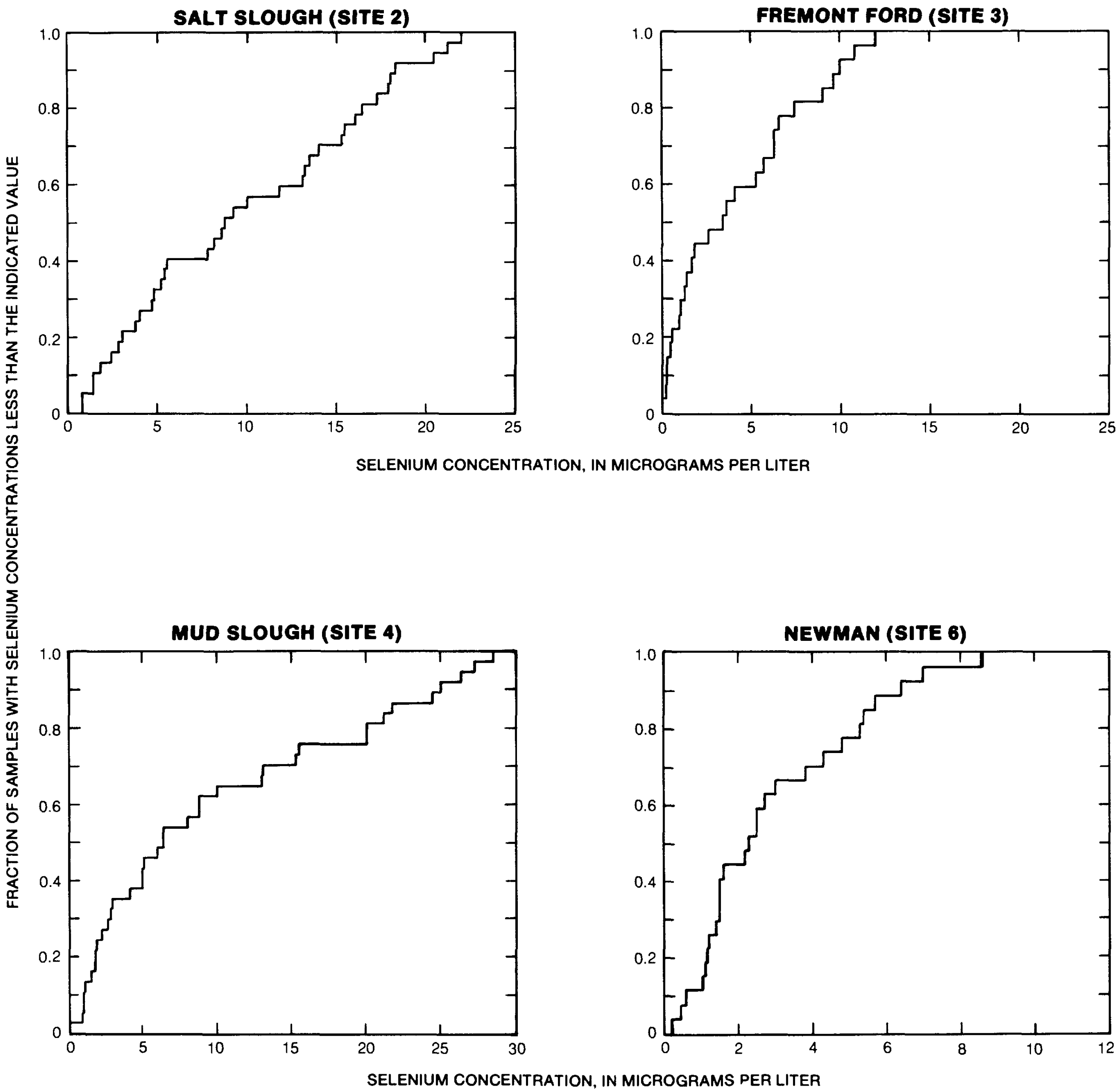

FIGURE 8. Cumulative frequency distributions for selenium concentrations.

San Joaquin River at site 3 and just upstream of site 6 more than 40 percent of the time. At site 6, where compliance may be monitored by the State, concentrations exceeded the 5 µg/L State interim objective more than 20 percent of the time. The 5 µg/L value also was occasionally exceeded at site 7 (8 percent) but not at sites 9 and 11 on the San Joaquin River. If the State water-quality

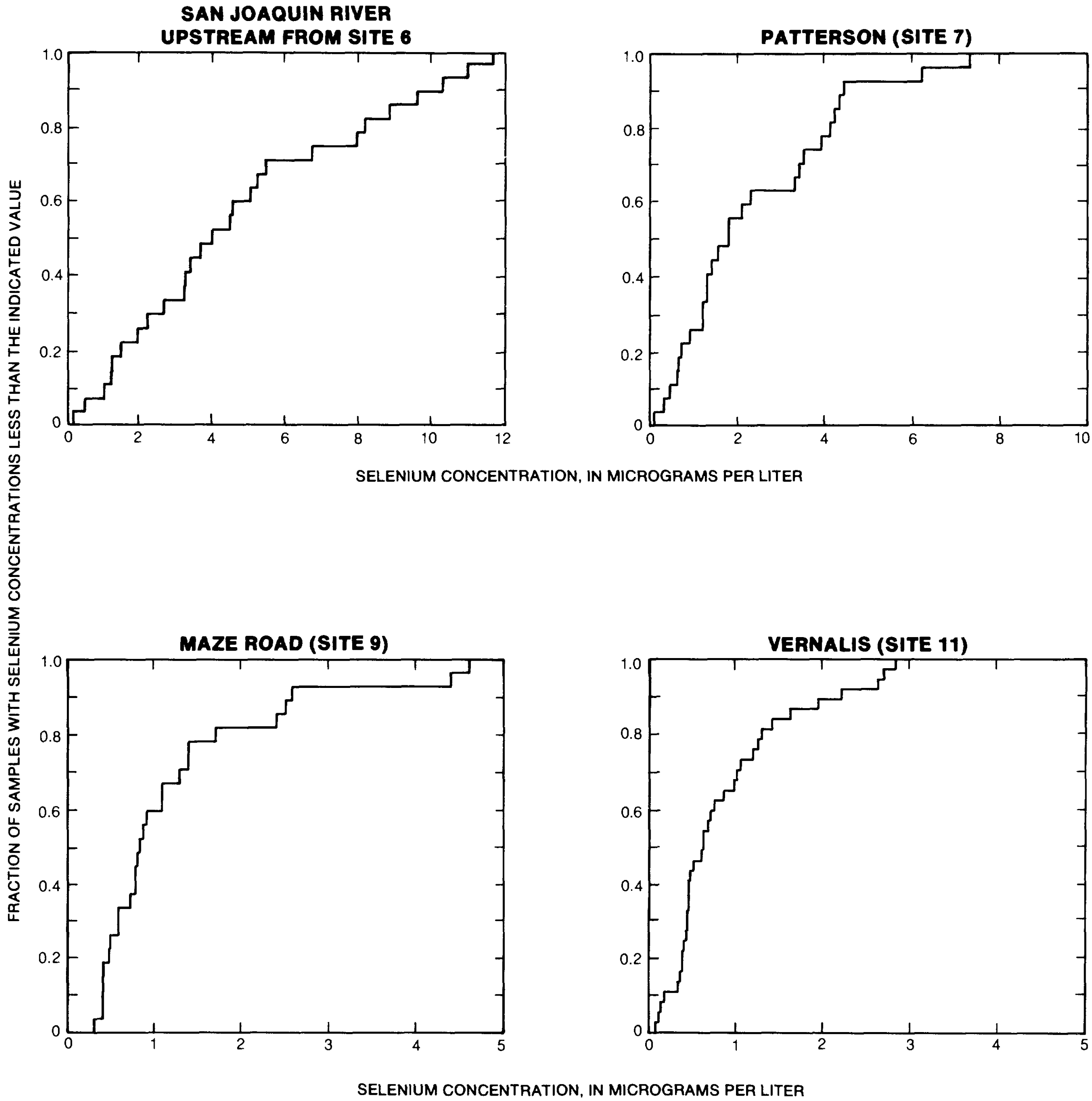

FIGURE 8. Cumulative frequency distributions for selenium concentrations--Continued.

objective for selenium was lowered to 2 µg/L, it would have been exceeded at all San Joaquin River sites, except site 1, 10 percent or more of the time during the study period. At Salt and Mud Sloughs and just upstream of site 6, 75 percent or more of the selenium concentrations were greater than 2 µg/L, and at sites 3 and 6, 55 percent were greater than 2 µg/L.

Correlation with Dissolved Solids and Streamflow

During the low-flow period, log-transformed selenium concentrations were correlated positively (α=0.05) with log-transformed dissolved solids in the San Joaquin River (sites 3, 6, 7, 9, and 11; r^2=0.34 to 0.68) and in Salt Slough (site 2; r^2=0.57). Selenium correlated similarly with specific conductance at the same sites. These correlations indicate that dissolved solids and selenium are partly associated with common sources. There was no correlation between selenium and dissolved solids in Mud Slough. Selenium and dissolved solids also were not correlated in the three eastside tributaries (sites 5, 8, and 10), where selenium concentrations are consistently low.

Although dissolved-solids concentrations were negatively correlated with streamflow, selenium concentrations were not significantly correlated (α=0.05) with streamflow during the low-flow period at any sites except site 3, for which there is a weak negative correlation (r^2=0.21), and Mud Slough (site 4), for which there is a weak positive correlation (r^2=0.23). Though both correlations were weak, the positive relation for Mud Slough indicates that selenium-enriched water is possibly an important source water during the higher flows of the low-flow period.

Analyses of the combined low-flow and high-flow periods resulted in correlations between dissolved solids, specific conductance, and selenium in the San Joaquin River similar to those during the low-flow period. Negative correlations between selenium and streamflow were significant at sites 3, 6, 7, 9, and 11 (r^2=0.14 to 0.66). These negative correlations for sites on the San Joaquin River result from the dilution effects of low-selenium water flowing into the river during the high-flow period.

SUMMARY AND CONCLUSIONS

During October 1985 through March 1987, two relatively distinct flow conditions occurred in the San Joaquin River: a low-flow period from October 1985 to mid-February 1986 and mid-May 1986 through March 1987, and a high-flow period from mid-February 1986 to mid-May 1986. Of total streamflow at the farthest downstream study site, the San Joaquin River near Vernalis, 49 percent occurred during the 15-month combined low-flow period and 51 percent during the 3-month high-flow period. The following conclusions summarize findings about streamflow, dissolved solids, and selenium during these periods.

- During the combined low-flow period, total streamflows from eastside tributaries accounted for 65 percent of flow at Vernalis; the upper San Joaquin River, 6 percent; Salt and Mud Sloughs, 9 percent; and within-reach gains from surface- and ground-water inflows about 20 percent.

- During the high-flow period, the relative contributions of flow from the eastside tributaries and the sloughs decreased to 53 and 3 percent, respectively, and the contribution of the upper San Joaquin River increased to 41 percent. Proportional within-reach gains were minimal.

- Despite the greater quantity of streamflow during the 3-month high-flow period, 76 percent of the dissolved-solids load and 65 percent of the selenium load occurred during the 15-month low-flow period.

- During the low-flow period, the combined dissolved-solids load of the eastside tributaries and the upper San Joaquin River was only 18 percent of the total load at Vernalis. The combined load of selenium from these sources was only 7 percent.

- In contrast to streamflow, most dissolved-solids load during low flow came from Salt and Mud Sloughs, which contributed 40 percent, and from within-reach sources of surface and ground water, which contributed about 42 percent.

- Selenium had a distribution of sources during low flow that was markedly different from both streamflow and dissolved solids. About 80 percent of selenium load at Vernalis was contributed from Mud and Salt Sloughs, and little was contributed from within-reach sources.

- During the high-flow period, the primary changes in sources of dissolved solids to the river were the increased contribution of the eastside tributaries and the upper San Joaquin River because of greater streamflow and the reduced relative contribution from within-reach sources. For selenium, the primary change was the increased contribution from the upper San Joaquin River.

- Dissolved-solids concentrations were highest in Salt and Mud Sloughs and decreased downstream with dilution from eastside tributaries. A State standard of 500 mg/L was exceeded 11 percent of the time in the San Joaquin River near Vernalis.

- Selenium concentrations also were highest in Salt and Mud Sloughs, which receive most subsurface drain water that enters the river. The U.S. Environmental Protection Agency's 4-day average aquatic-life criterion of 5 µg/L of selenium was exceeded in more than 60 percent of the samples from the sloughs and in about 20 percent of the samples from the San Joaquin River, just downstream of the Merced River.

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