SOURCES OF DISSOLVED AND PARTICULATE SUBSTANCES TO THE SACRAMENTO RIVER NEAR SACRAMENTO, CALIFORNIA, SUMMER, 1985

By Laurence E. Schemel, Allan Y. Ota, Stephen W. Hager,
and Alan M. Swithenbank

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ABBREVIATIONS AND UNITS

Specific Conductance Sp. Conduct., SPEC. COND.	microsiemens per centimeter (uS/cm)
Alkalinity ALKALIN	milliequivalents per liter (meq/L)
Nitrite NO_2^-	micromoles per liter (umol/L)
Nitrate NO_3^-	micromoles per liter (umol/L)
Ammonium NH_4^+	micromoles per liter (umol/L)
Phosphate PO_4^{3-}	micromoles per liter (umol/L)
Dissolved silica SiO_2, D. Silica	micromoles per liter (umol/L)
Suspended particulate matter S. PART. MATTER, SPM	milligrams per liter (mg/L)
Total nitrogen TOTAL N, T. Nitrogen	micromoles per liter (umol/L)
Dissolved nitrogen DISSOL. N, D. Nitrogen	micromoles per liter (umol/L)

Total phosphorus TOTAL P, T. Phosphorus	micromoles per liter (umol/L)
Dissolved phosphorus DISSOL. P, D. Phosphorus	micromoles per liter (umol/L)
Particulate carbon PART. C, P. Carbon	micromoles per liter (umol/L)
Particulate nitrogen PART. N, P. Nitrogen	micromoles per liter (umol/L)

CONVERSION FACTORS

Metric units are used in this report. For readers who prefer inch-pound units, the conversion factors for the terms used in this report are listed below.

Multiply	By	To obtain
um (micron)	0.000003937	inch
mm (millimeter)	0.03937	inch
cm (centimeter)	0.3937	inch
m (meter)	3.281	foot
ug (microgram)	0.000001	gram
mg (milligram)	0.001	gram
g (gram)	0.002205	pound
uL (microliter)	0.000001	liter
mL (milliliter)	0.001	liter
L (liter)	0.2642	gallons
kPa (kilopascal)	0.007376	foot-pounds

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ABSTRACT

Concentrations of 14 dissolved and particulate substances (alkalinity, nitrate, nitrite, ammonium, phosphate, dissolved silica, specific conductance, dissolved nitrogen, dissolved phosphorus, particulate nitrogen, total nitrogen, total phosphorus, particulate carbon, and suspended particulate matter) were measured at five locations in the Sacramento River, Feather River, and Colusa and Sutter agricultural drains during a seven-week period of late summer, 1985. The totals of the mean transports from the agricultural drains were greater than those from the tributary rivers for all substances except dissolved silica. Major variations in transports from the agricultural drains were consistent with variations in concentrations and transports at the downstream Sacramento River location.

Variations in concentrations with respect to distance downstream were measured on one day in the reach of the Sacramento River from Knights Landing to a location upstream of Rio Vista. Concentrations of substances in the Sacramento River changed as a result of inflows from agricultural drains, a major municipal waste treatment facility, and tributary rivers. Inflows from agricultural drains increased concentrations of alkalinity, suspended particulate matter, particulate carbon and nitrogen, and specific conductance, and inflows of municipal waste increased concentrations of ammonium and phosphate. Inflows from tributary rivers decreased concentrations of most substances. Results also indicated that concentrations of some substances in the Sacramento River were changed by biological and chemical transformations, such as nitrification of ammonium to nitrate.

INTRODUCTION

The Sacramento River is a major freshwater resource for the state of California and the major freshwater inflow to San Francisco Bay, the largest estuary in the state (fig. 1). Development of this freshwater resource has been important to growth in California for over a century (Hutchinson, 1980). For example, major reservoirs on tributaries of the Sacramento River have increased the availability of water during the dry summer months, and thus have increased the potential for irrigated agriculture and population growth.

Development of the drainage basin of the Sacramento River and management of reservoirs and water conveyance facilities are responsible for major changes in the seasonal flow pattern of the Sacramento River near Sacramento and the annual amount and seasonal pattern of flow to San Francisco Bay. Reservoirs impound snowmelt during spring, thus reducing or practically eliminating a major freshet (Kahrl, 1978). This water is released primarily during summer, resulting in flows near Sacramento (and perhaps to San Francisco Bay) that are higher than estimated historical flows. More than half of the flow of the Sacramento River during summer is diverted downstream from Sacramento and does not flow into San Francisco Bay.

In addition to changes in seasonal flow patterns, concentrations and transports (products of flow and concentration) of dissolved and particulate substances in the Sacramento River are influenced by activities in the drainage basin. In particular, inputs of agricultural and municipal wastes increase concentrations of various dissolved and particulate substances in the Sacramento River as it flows southward through the Sacramento Valley (California Department of Water Resources, 1962). In a few cases, variability in the inputs from major agricultural drains during summer (Tanji, 1981) appear to contribute to changes in chemical gradients in San Francisco Bay (Schemel and Hager, 1986).

This report quantifies major sources that influence concentrations and transports of substances in the Sacramento River flow that eventually enters San Francisco Bay during late summer. Samples were collected during late summer of 1985 in the reach of the Sacramento River that is most affected by inflows from two major agricultural drains, the Colusa and Sutter Basin drains, and waste inflow from the Sacramento metropolitan area to quantify the supply to the river of 14 dissolved and particulate substances: alkalinity, nitrate, nitrite, ammonium, phosphate, dissolved silica, specific conductance, dissolved nitrogen, dissolved phosphorus, particulate nitrogen, total nitrogen, total phosphorus, particulate carbon, and suspended particulate matter. Detailed studies involving less frequent sampling, typically monthly, have described major sources that affect water quality in the Sacramento River (California Department of Water Resources, 1962; California Regional Water Quality Control Board, 1979), and changes in water quality, primarily salinity, have been simulated with mathematical models (California Department of Water Resources, 1971). This study documents variability in the inputs from the major agricultural drains during late summer in greater temporal detail than in previous studies, which is of interest to chemical studies in San Francisco Bay. This

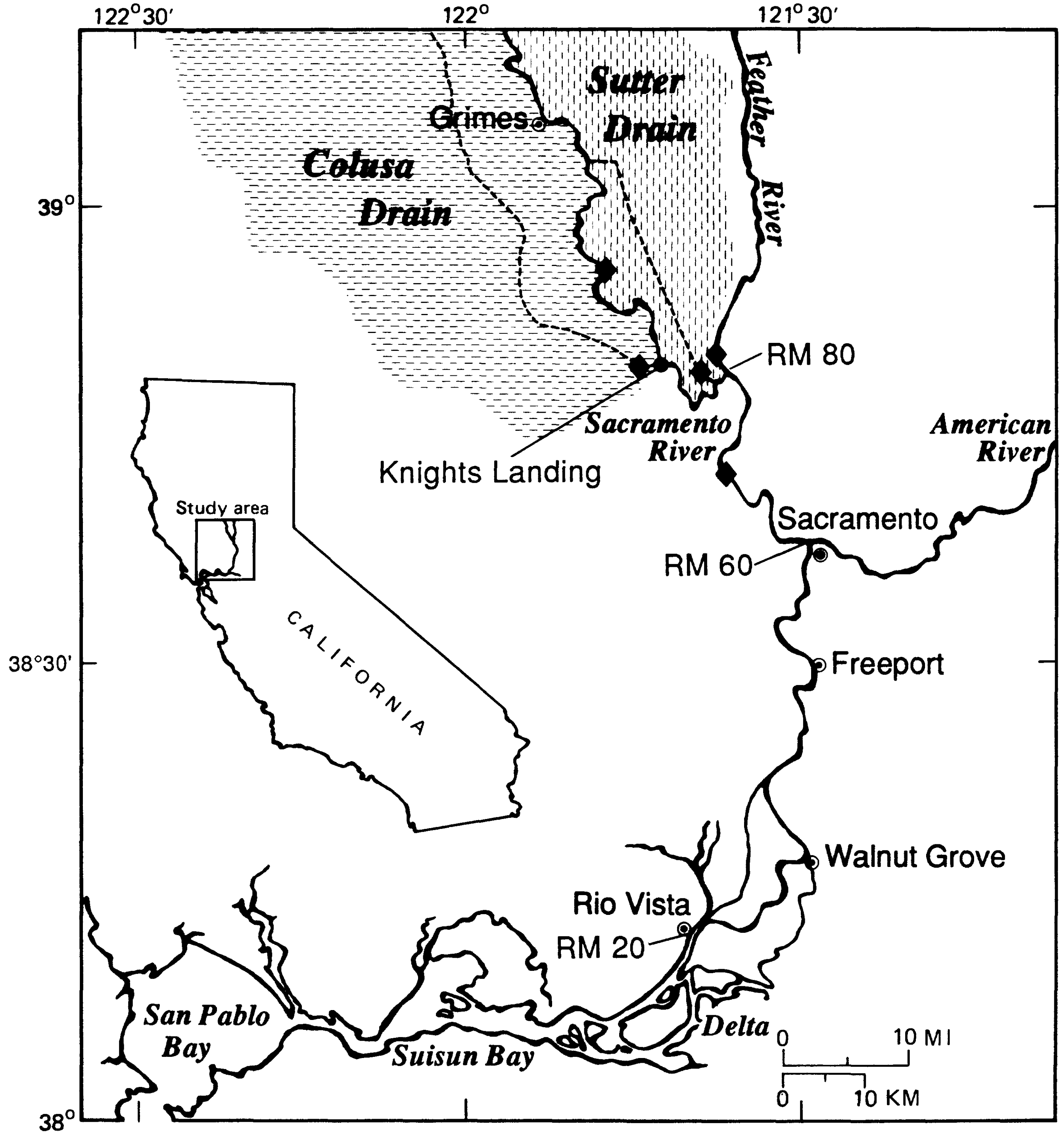

Figure 1. Map of study area showing locations of five stations upstream of Sacramento (diamonds) and northern embayments of San Francisco Bay.

report is limited to presentation of the data and methods, and to a preliminary description of the results.

Acknowledgments

The authors thank the California Department of Water Resources, California District Office of the U. S. Geological Survey, W.H.Kido (Sacramento Regional Wastewater Treatment Plant), and K.K.Tanji (University of California, Davis) for providing information used in this report. Reviews of the manuscript by Ronald Avanzino and Christopher Foe are greatly appreciated. We extend a special thank you to Brian Swarthout for assistance with the field sampling and in the laboratory.

METHODS

Flow rates shown in this report were obtained from the California Department of Water Resources at Red Bluff (Colusa and Sutter drains), and the U. S. Geological Survey California District Office, Sacramento (various locations on the Sacramento River and the American River at Sacramento; figs. 1 and 2). Flow rate was not measured on the Feather River near its confluence with the Sacramento River or at the Lower Sacramento River station. Flow rates for the Feather River were computed by difference: Feather River flow = Sacramento River flow at Freeport - (American River flow at Sacramento + Sacramento River flow at Grimes + combined flows of Colusa and Sutter Basin drains). Flow rates at the Lower Sacramento River station were computed as the difference between the Sacramento River flow at Freeport and the American River flow at Sacramento.

Near-surface water was sampled from a small boat at selected locations on the Sacramento River in the reach between Knights Landing and Rio Vista on August 27, 1985. Samples also were collected from a boat in the Feather and American Rivers at locations just upstream of their confluences with the Sacramento River. All samples were kept cool during transport to the laboratory and were processed on the following day.

Near-surface water was collected twice weekly at five stations, designated upper Sacramento River, Feather River, Colusa drain, Sutter drain, and lower Sacramento River, from August 19 through September 26, 1985 (fig. 1). A simple rope and plastic bucket assembly was used from overhanging structures at the two drain locations. The bucket was thrown to the limit of the rope and drawn in quickly at the river stations. Water was decanted into linear-polyethylene bottles that were kept cool during transport to the laboratory for processing. Samples from these five locations were always collected and processed on the same day.

Sample Processing and Analytical Methods

Nutrients

Samples for dissolved inorganic nutrient analysis were filtered through 47mm diameter, 0.4 um pore-size Nuclepore (1) polycarbonate membrane filters under vacuum (less than 17 kPa). Filtered samples were frozen in 30 mL amber Nalgene linear-polyethylene bottles that had been preconditioned by soaking in a 2.5 meq/L solution of sodium bicarbonate. Samples were thawed at room temperature for at least 12 hours and vigorously shaken before analysis.

Concentrations of ammonium, nitrate, dissolved reactive phosphate (subsequently referred to as phosphate), and dissolved silica were measured simultaneously on a Technicon AutoAnalyzer II system. With the exception of dissolved silica, analyzer responses were linear over the ranges of concentrations encountered in this study. Samples were referenced to upscale standards and blanks that were analyzed at two- to

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(1) The use of brand names is for identification purposes only and does not constitute endorsement by the U. S. Geological Survey.

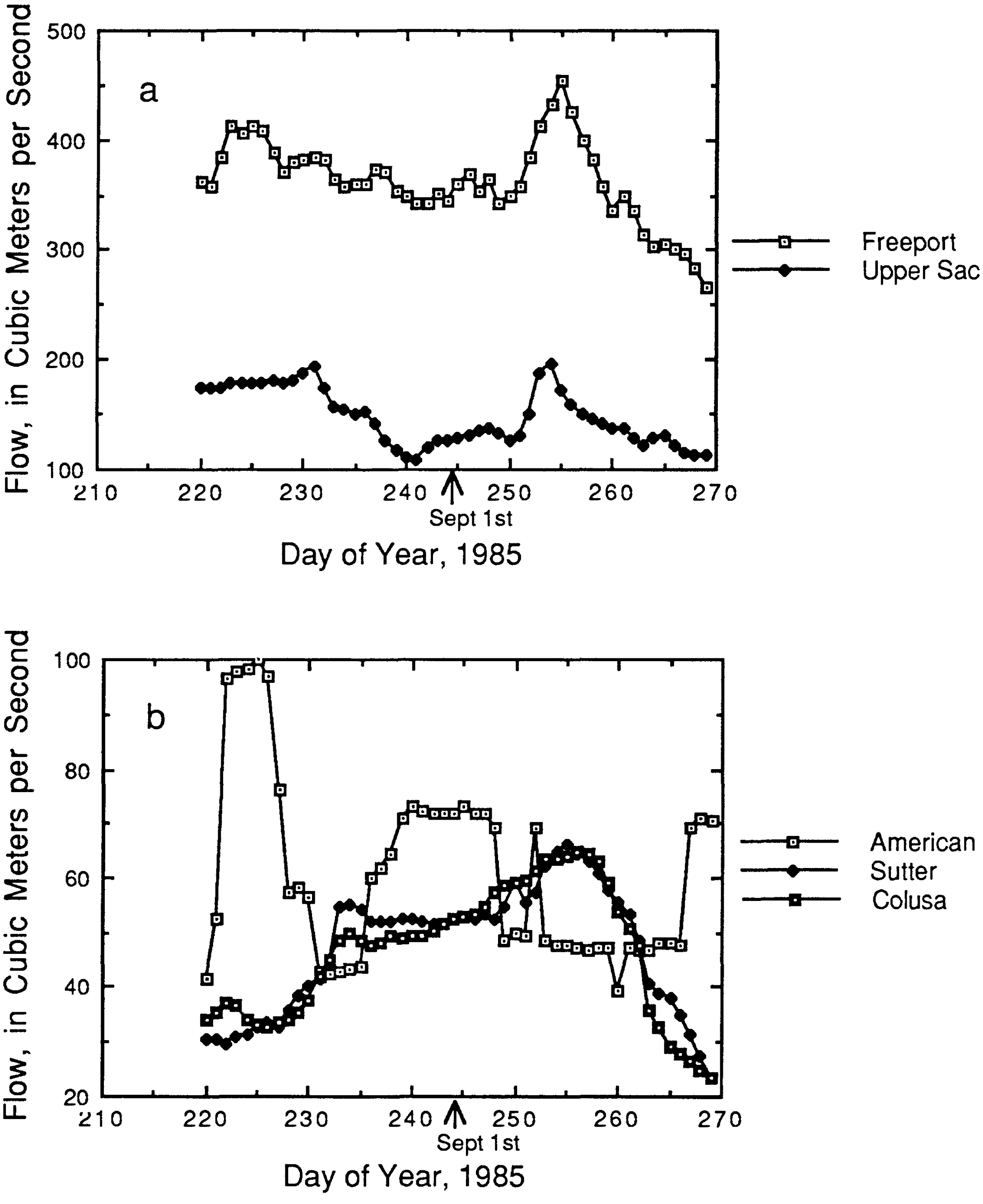


Figure 2. Flow, in cubic meters per second, at five stations: (a) Freeport and upper Sacramento River stations and at (b) American, Sutter drain, and Colusa drain stations during August and September of 1985.

four-hour intervals. Standards were prepared in artificial river water (1.0 meq/L solution of sodium carbonate). All five analyses were performed at constant temperature by using a Tecam Circulator C-40, which continuously pumped 37° C water through specially-designed heating tubes inserted through the centers of the glass mixing coils on each manifold.

The ammonium method was an automated version of the phenol-hypochlorite method of Solorzano (1969) using a heating bath temperature of 37°C, as recommended by Berg and Abdullah (1977). This temperature and the increased reaction time resulting from the addition of ten-turn coils in place of five-turn coils and two additional twenty-turn coils before the heating bath gave maximum color development and low blanks. Typical precision was + or - 0.2 umol/L.

The nitrate + nitrite method was the Technicon (1973) method number AII-100-70W with one twenty-turn coil added to increase reaction time for better color stability. The life of the cadmium column was prolonged by the addition of 0.121 g copper sulfate per 20 liters of ammonium chloride solution, as suggested by Connors and Beland (1976). The pH of this reagent was not adjusted. Typical precision was + or - 0.1 umol/L. Nitrate was calculated by subtracting the corresponding concentration of nitrite from the results of this analysis.

The nitrite method was an adaptation of the Technicon (1973) method number AII-100-70W with the cadmium column removed. To fit all five analyses for nutrients on a single proportioning pump, the sample-ammonium chloride mixture was drawn from the debubbler which preceded the cadmium column in the nitrate + nitrite analysis. Typical precision was + or - 0.05 umol/L.

The dissolved silica method was a modification of the Technicon (1976) method number AII-105-71W. To reduce nonlinearity at high concentrations, a sample tube with half the original delivery rate was used. Reaction time was increased to give maximum color development by adding a ten-turn coil after the addition of ascorbic acid. A blank and six upscale standards were used to elucidate the standard curve. Calculations were based on a second-order least-squares fit to the data. Typical precision was + or - 1 umol/L.

The phosphate method was a modification of that of Atlas and others (1971), using ascorbic acid (70 g plus 50 mL acetone per L of solution) as a reductant. This modification allowed analysis of samples predigested with hydrogen peroxide in ultraviolet light, as described below. To increase reaction time for maximum color development, ten-turn coils replaced the five-turn coils and a twenty-turn coil replaced the ten-turn coil in the manifold design. Typical precision was + or - 0.05 umol/L.

At each station, one sample each week was processed for total nitrogen (TN), total phosphorus (TP), dissolved nitrogen (DN) and dissolved phosphorus (DP). Total (unfiltered) and dissolved (filtered through glass fiber filter) samples were digested prior to analysis using hydrogen peroxide and ultraviolet light. The method is described for nitrogen by Hager and Harmon (1984). After digestion, samples were analyzed by the methods given above. Because hydrogen peroxide and ultraviolet light digestion does not mineralize all forms of nitrogen, and because the "total" samples were membrane filtered before analysis, thus removing particle-adsorbed phosphorus, TN and TP both could underestimate the total amounts of these elements that were present.

Specific Conductance and Alkalinity

The sample for alkalinity and specific conductance analysis was stored in a plastic quart bottle for less than 24 hours before sample processing. An unfiltered aliquot was transferred to a 250 mL glass bottle with poly-seal cap for later specific conductance determination. Alkalinity samples were stored in 250 mL wide mouth plastic bottles after filtration through glass fiber filters. Filters were rinsed twice with sample water before the aliquot for analysis was taken. Alkalinity samples were stored at room temperature in the dark for periods ranging from a few days to months. Effects of sample storage were not tested. Results of Brewer and Goldman (1976) and Goldman and Brewer (1980) indicate that the changes in total alkalinity would be less than 0.050 meq/L.

Specific conductance was determined at $25^{o}C$ with an inductive bench salinometer (Beckman Model RS7B) relative to standard seawater (P72, I.A.P.S.O. Standard Seawater Service, Institute of Oceanographic Sciences, England). The precision of the method was not rigorously tested, but the sensitivity of the instrument corresponded to a precision of about 5 microsiemens per cm (uS/cm) or less.

Alkalinity was determined by titration at $25^{o}C$ (Gran, 1952). The method and apparatus was the same as that described by Schemel (1984) with the exception that a Brinkman semi-automated buret was used to add 0.010 mL aliquots of 0.5N HCl to the samples. The digital output of the buret was modified, as described in the instruction manual, so that titrant volumes could be read to 0.1 uL. Bicarbonate end points were usually reached with 0.3 to 0.4 mL of titrant. The largest error in the analysis was in the determination of the titrant concentration; we estimate this uncertainty to be about 0.2 percent of the reported concentrations. Other errors were described by Schemel (1984).

Suspended Particles

Concentrations of suspended particulate matter (SPM) were determined gravimetrically. An aliquot of sample water was vacuum filtered through a preweighed 47 mm-diameter, 0.45um pore-size Nuclepore filter. The filter was air dried for a minimum of four weeks, then reweighed. After additional drying time the filter was again weighed. Precision for the SPM analysis was not determined, but previous results gave a typical mean deviation for duplicates of less than 1 mg/L (Hager and Harmon, 1984).

For particulate nitrogen (PN) and particulate carbon (PC), duplicate sample aliquots of between 26 and 318 mL (depending on sediment concentration) were vacuum filtered through precombusted (at $450^{o}C$) 13 mm-diameter glass fiber filters (Gelman type A-E). Filters were placed on precombusted 47 mm-diameter filters to wick residual water, then folded and inserted into precombusted nickel capsules. These capsules were placed individually in small glass vials and stored in a dessicator over silica gel or magnesium perchlorate until analysis.

PN and PC samples were analyzed with a Perkin-Elmer model 240C elemental analyzer equipped with an autosampler. Samples were combusted at 950°C. Blanks were run about every five to ten samples, standards (acetanilide) about every 15 to 20 samples. Blanks and standards were averaged for each half-day run. Sample concentrations were calculated as the sample reading minus the sum of the instrument zero reading and the blank, divided by the standard factor. Instrument (carrier gas and ladle) blanks were stable and low through most of the analyses, rarely varying more than 0.5 ug for N, equivalent to 1 umol/L for a 30 mL sample or 0.1 umol/L for a 300 mL sample.

RESULTS FROM THE TRANSECT OF THE SACRAMENTO RIVER FROM KNIGHTS LANDING TO THE DELTA

Results are shown as concentrations relative to distance in fig. 3, and numerical values are tabulated in the appendix. The river-mile (RM:) distance scale, as defined by the state of California Department of Water Resources (1962), is used because it is common to many studies of the Sacramento River. Results are described here relative to reaches of the river that receive inflows from : a) Colusa drain (near RM:90), b) Sutter drain (near RM:81) and the Feather River (near RM:80), c) American River (near RM:60), and d) municipal waste from the Sacramento Metropolitan area that enters the Sacramento River near Freeport (near RM:47; fig. 1).

Specific conductance and alkalinity increased in the reach that receives flow from the Colusa drain, then decreased below the confluences with the Feather and American Rivers. Concentrations varied only slightly at locations downstream of RM:58.

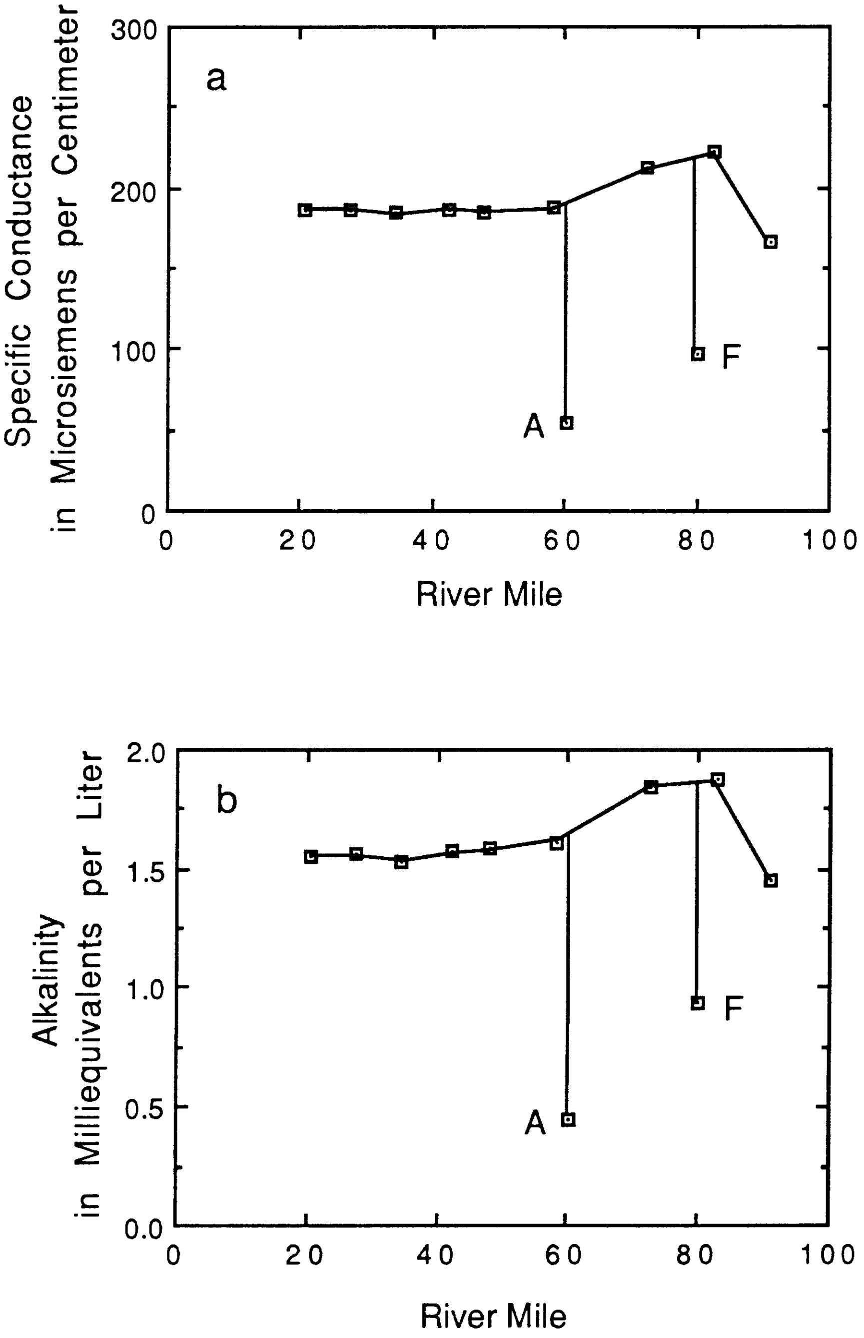
Concentrations of dissolved silica were highest at the farthest upstream location, then decreased in the reaches that receive flow from the drains and the Feather and American Rivers. Concentrations of dissolved silica varied little at locations downstream of RM:58.

Concentrations of phosphate increased in the reach that receives flow from the Colusa drain, but showed little change below the confluences with the Feather and American Rivers. A large increase in concentration was observed in the reach that receives municipal waste inflow, and concentrations remained high at locations downstream.

Concentrations of ammonium were low at the farthest upstream Sacramento River location, then increased slightly in the reaches that receive flows from the drains and the Feather and American Rivers. A large increase in concentration was observed in the reach immediately downstream of the municipal waste inflow, then concentrations progressively decreased at locations downstream.

Concentrations of nitrate and nitrite showed similar variability with distance. Nitrate was much more concentrated than nitrite, and only variability in nitrate is described here. Concentrations of nitrate increased in the reach that receives flow from the drains and Feather River and decreased in the reach that receives flow from the American River. Little increase in concentration was observed just

Figure 3. Measurements of properties, dissolved and particulate nutrient concentrations, and suspended particulate concentrations along a transect from Knights Landing to Rio Vista. Measurements are (a) specific conductance in microsiemens per centimeter, (b) alkalinity in milliequivalents per liter, (c) dissolved silica in micromoles per liter, (d) dissolved reactive phosphate in micromoles per liter, (e) ammonium in micromoles per liter, (f) particulate nitrogen in micromoles per liter, (g) nitrate in micromoles per liter, (h) nitrite in micromoles per liter, (i) particulate carbon in micromoles per liter, and (j) suspended particulate matter in milligrams per liter, at selected locations in the reach of the Sacramento River between Knights Landing (river mile 90) and Rio Vista (river mile 12) on August 27, 1985. Results from the American and Feather Rivers are indicated as "A" and "F", respectively.



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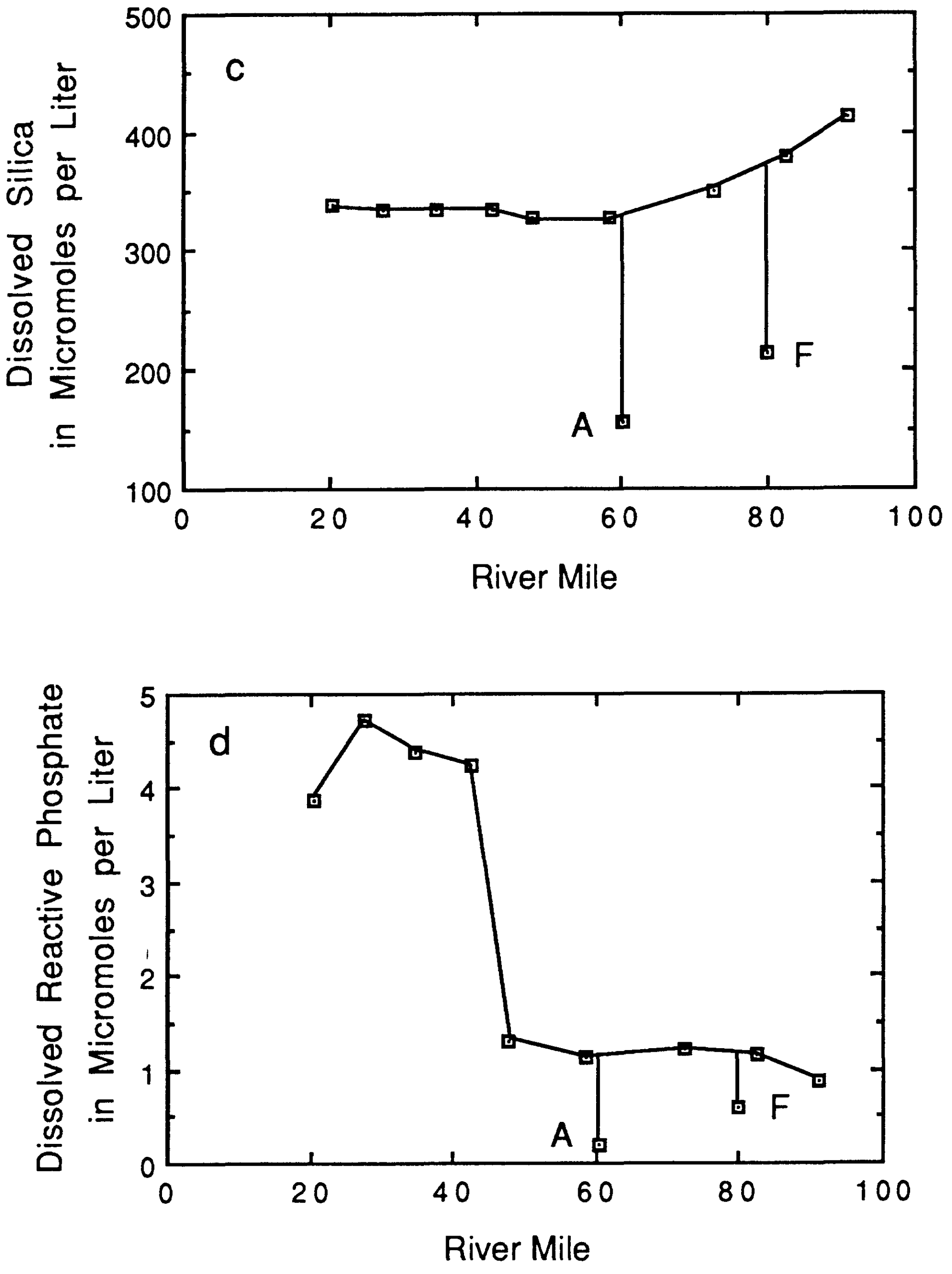

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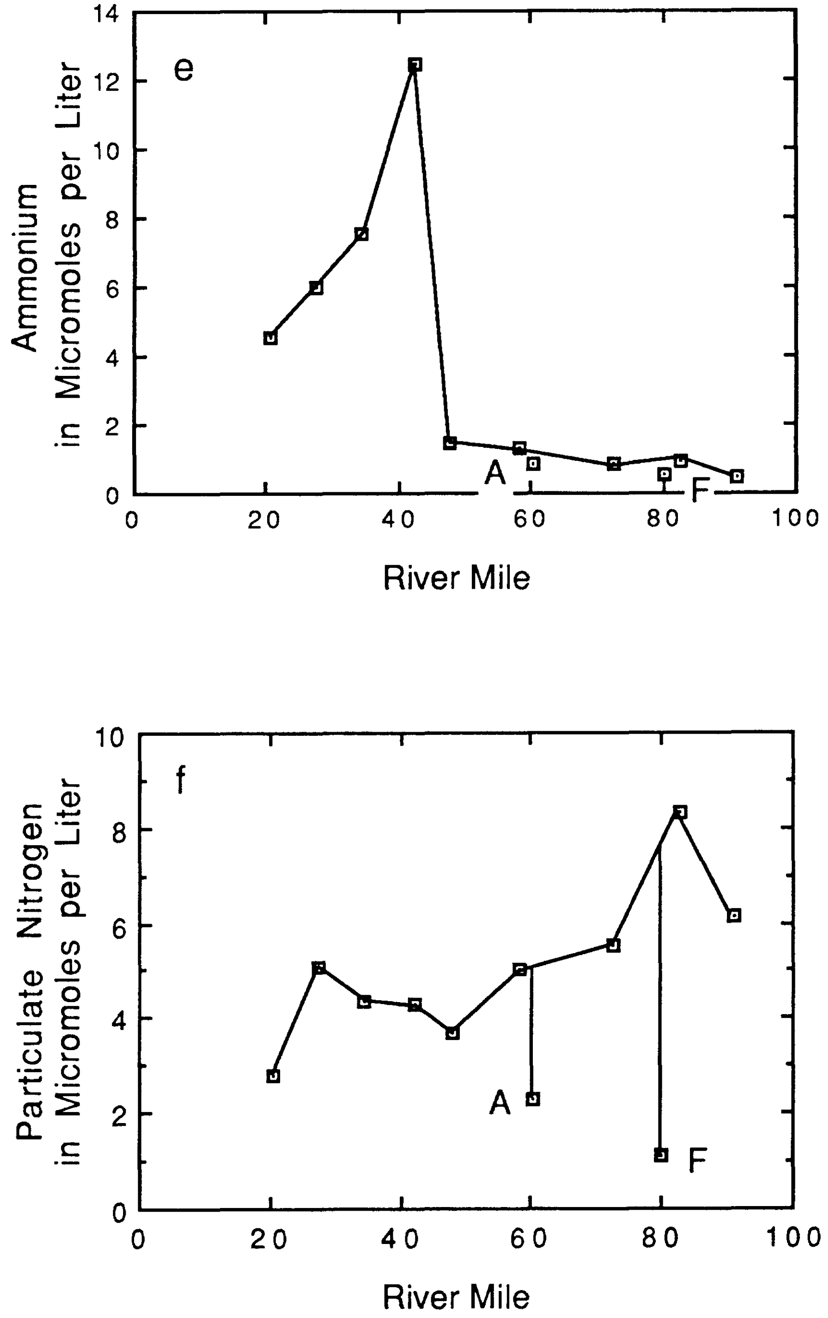

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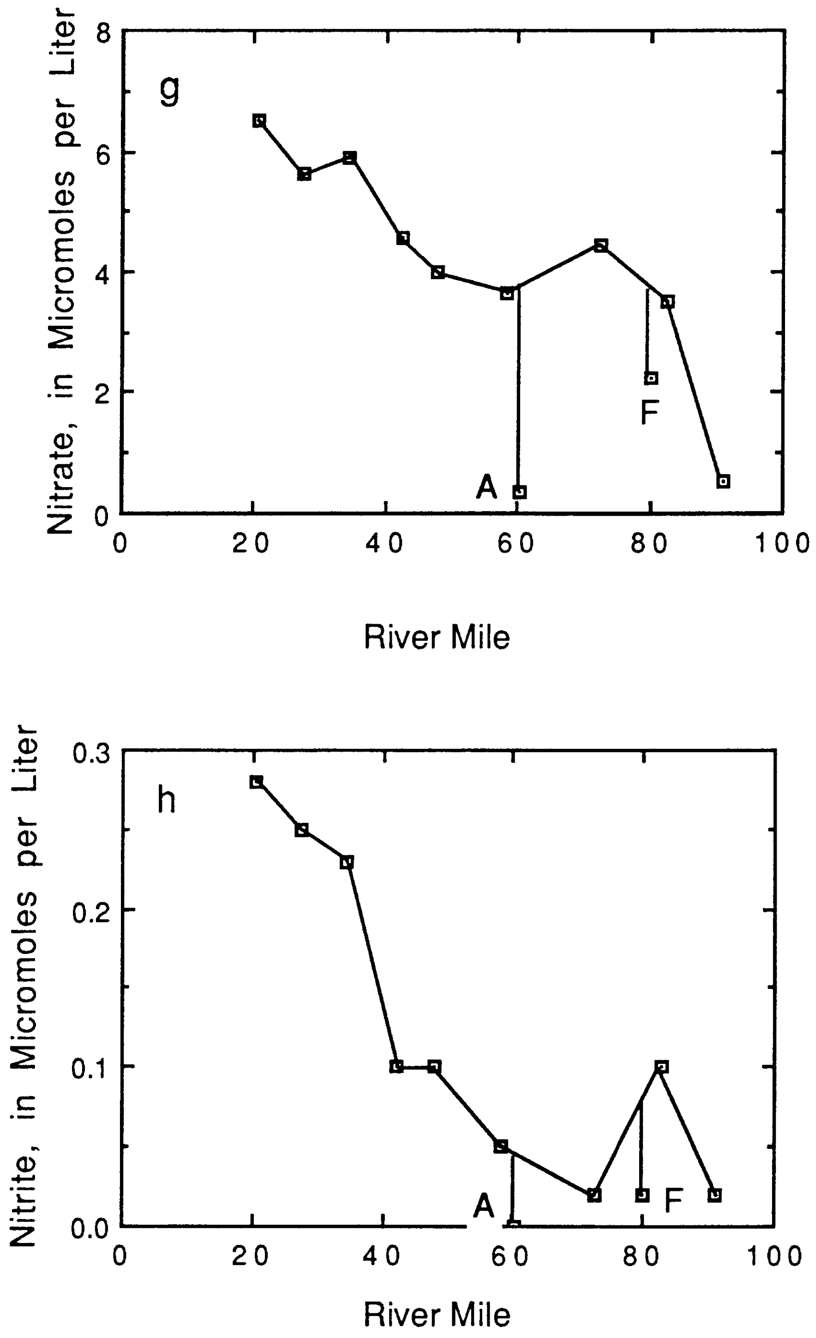

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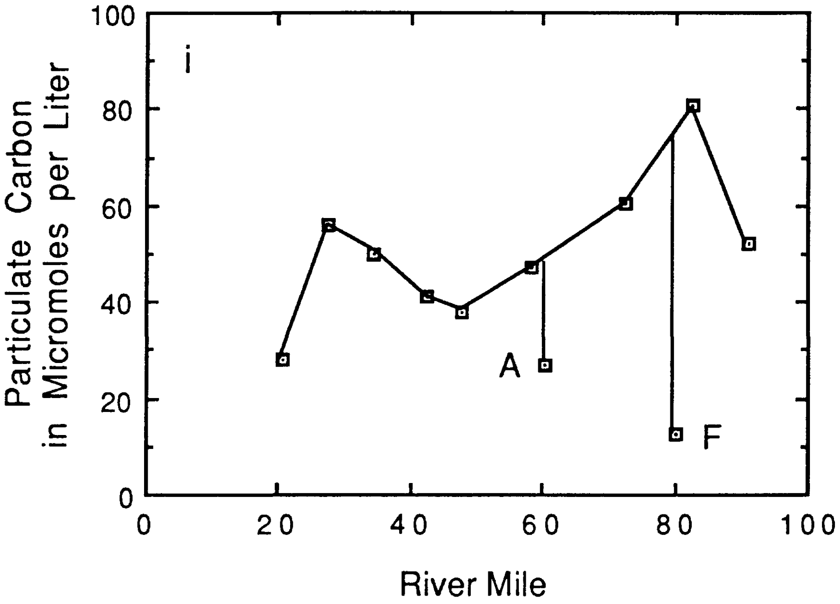

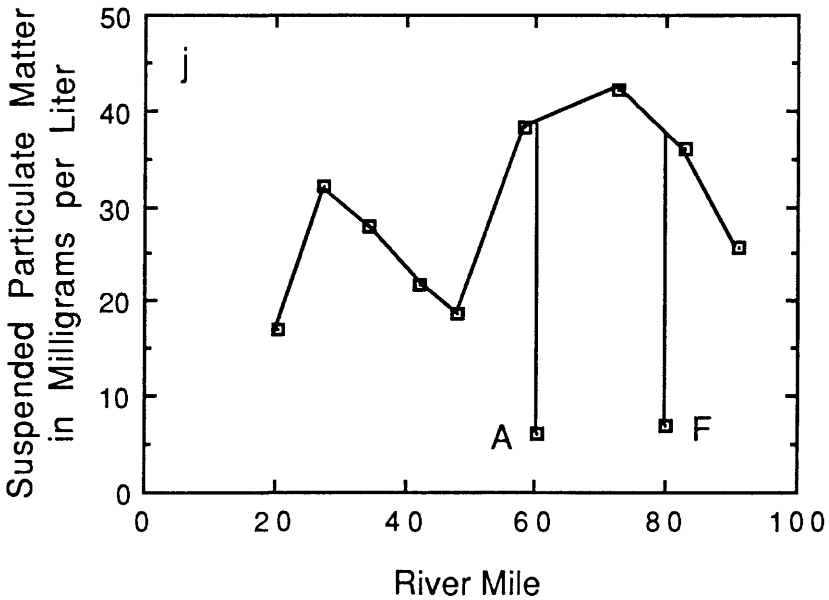

Figure 3.-- continued.

downstream of municipal waste inflow, but, in contrast to ammonium, concentrations of nitrate progressively increased at locations downstream.

Concentrations of particulate carbon (PC) and particulate nitrogen (PN) increased in the reach that receives inflow from the Colusa drain and decreased downstream of the confluences with the Feather and American Rivers. Variability in concentrations of PC and PN in the reach below the municipal waste inflow was similar to that for SPM. Lowest concentrations of PN, PC, and SPM in the Sacramento River were found at the farthest downstream location.

Concentrations of suspended particulate matter (SPM) increased in the reaches that receive flow from the agricultural drains and the Feather River. Concentrations of SPM decreased in the reach below the confluence with the American River, but increased in the reach that receives municipal waste and at locations downstream. Concentrations of SPM decreased at the farthest downstream location.

DISCUSSION OF RESULTS FROM THE TRANSECT OF THE SACRAMENTO RIVER

Results from previous studies have shown that changes in concentrations of solutes along this transect of the Sacramento River are primarily caused by mixing with various inflows and by chemical transformations in the water as it flows toward San Francisco Bay (California Department of Water Resources, 1962). Similarly, our data showed that tributary river inflows generally decreased concentrations of most substances, and that the major agricultural drains and municipal waste inflows increased concentrations of many substances. From the observed variability in concentrations, it appeared that inflow from agricultural drains was a major source of salts (specific conductance), alkalinity, SPM, PN, and PC, and that the inflow of municipal waste near Freeport was a major source of ammonium and phosphate; both were sources of nitrite. In contrast, the (upstream) Sacramento River was the major source of dissolved silica.

Inflow from agricultural drains was a source of nitrate, but additional sources also appeared important. The decrease in ammonium and increase in nitrate that was observed downstream of the inflow of municipal waste was similar to patterns observed in the Potomac River (Elkins and others, 1981) and in the Choptank River in Maryland (Ward and Twilley 1986) that have been attributed to nitrification of ammonium. Data supplied by the Sacramento Regional Wastewater treatment plant (written communication, September 1985) indicated that during August 1985 the average composition of the effluent from this plant would have increased ammonium concentrations in the Sacramento River by about 11 umol/L, the same as the increase observed in our study. In addition, the effluent would have increased nitrate concentrations by only 0.2 umol/L, and our data showed an increase of about 0.6 umol/L. We estimated that the travel time between the municipal waste input and our farthest downstream location was about 3.5 days. The corresponding loss rate for ammonium in that reach of the river was 2.3 umol/L per day; that for the increase in nitrate was only 0.55 umol/L per day (0.61 umol/L per day for the increase in nitrate plus nitrite). Because the increase in nitrate was equivalent to less than half of the loss of ammonium, other processes which were not evaluated in this study might account for the loss of ammonium in this reach of the river (for example, removal by plants).

RESULTS FROM THE FIVE STATIONS LOCATED UPSTREAM OF SACRAMENTO

During summer and fall, flows in the tributaries of the Sacramento River are controlled largely by reservoir releases, withdrawals for agricultural and municipal uses, and inflows of drainage waters. In general, flows in the tributaries during the irrigation season (April to October) are higher and perhaps more variable than historical flows, in response to the needs of water users. Flows at the upper Sacramento River station and at Freeport (fig. 2a) showed a general decrease during the month of August, then a peak in flow in September followed by a large decrease in flow through the end of the study. Flows at the Colusa and Sutter drain stations (fig. 2b) showed an increase in flow to maximum values that coincided with the peak in flow of the Sacramento River in September, followed by decreasing flows to the lowest values observed by the end of the study. This pattern of variability in flow at the drain stations is typical. Factors causing this variability are described by Tanji and others (1975 and 1980).

Variability in the concentrations of dissolved and particulate substances during August and September are shown for the five stations in fig. A of the appendix. Variability in concentration for a substance at a single station was small in most cases, but significant in a few. With the exception of nitrate, ranges of concentrations in the drains were greater than those in the rivers. In general, concentrations in both drains increased over the period of the study. A similar trend was not as clear at the river stations, where concentrations of some substances were highest during the middle of the study period.

Regardless of variability in concentration, there were consistent differences among the concentrations at the five stations over the study period. Concentrations at the Feather River station were less than those at other stations for all substances except the dissolved inorganic nitrogen species, nitrate, nitrite, and ammonium. For these three substances, concentrations at the Feather River station exceeded only those at the upper Sacramento River station. Concentrations at the lower Sacramento River station were consistently higher than those at the upper Sacramento River station for all substances except dissolved silica.

Concentrations at the Colusa and Sutter drain stations were consistently higher than those at the three river stations for all substances except dissolved silica. Concentrations of dissolved silica at the Sutter drain station were the highest of the five stations, whereas those at the Colusa drain station were similar to concentrations at the upper and lower Sacramento River stations.

Concentrations of nitrite were similar at both drain stations over most of the study period; however, there were major differences in concentrations of the other substances between the two stations. These differences, as shown in fig. A of the appendix, were not always consistent, and variability in concentrations at the drain stations was substantial in a few cases. In general, concentrations of PN, PC, SPM, TN, DN, and nitrate were higher at the Colusa drain station, and concentrations of TP, DP, phosphate, dissolved silica, and ammonium and specific conductance and alkalinity were higher at the Sutter drain station.

Mean values, ranges, and coefficients of variation (standard deviation divided by the mean) for concentrations (and transports) of dissolved and particulate substances at the five stations are given in Tables 1-5. Magnitude of the variability in concentration over the study period is examined here primarily by comparing the coefficient of variation for each substance to that for flow.

In general, concentrations of most substances showed about the same or less variability as that for flow. Concentrations of dissolved silica showed the least variability relative to the other substances at all of the stations. Coefficients of variation for alkalinity and specific conductance also were consistently low at all stations except at the Sutter drain station, where alkalinity was less variable than flow, and specific conductance was as variable as flow. Although some substances showed high coefficients of variation at one or two stations, there was no consistent pattern among the stations.

Transport rates are the product of concentrations and flow. Consequently, transports are generally more variable than flow because of the variability in each of the factors (Tables 1-5). Exceptions can occur when flow and concentration are inversely related. By examining simple correlation between concentration and the dilution factor, (flow)$^{-1}$, the possibility of dilution by flow can be evaluated. Concentrations of ammonium at the Colusa drain station and concentrations of PN at the upper Sacramento station were the only cases where variability in concentration was substantially greater than variability in transport. In both cases, high correlation of concentration with (flow)$^{-1}$ was observed. Correlation coefficients (r) were 0.90 for ammonium and 0.73 for PN. There were a few cases where variability in flow and transport were about the same. One of these, transport of nitrate at the Colusa drain station, also showed high correlation (r=0.76) with the dilution factor.

As noted above, flows at the drain stations increased over the period of the study to maximum values about two weeks before the end of the study, then flows decreased to the lowest values observed. Similarly, transports of all substances at the drain stations (except for ammonium at the Colusa drain station) generally increased with time until the last two weeks of the study, then decreased to lowest values observed (appendix fig. B). This pattern was observed also at the lower Sacramento River station for all substances, and at the upper Sacramento River station for nitrite, nitrate, DN, and TN. Transport variability at the upper Sacramento River station was somewhat similar to that for flow in the cases of phosphate and ammonium, and a very large peak in transport of nitrate corresponded to the peak in flow rate.

From the day of the highest flows to the last day of the study, there was a 48 percent decrease in total flow, comprising a 40 percent decrease in the combined flow at the Sutter and Colusa drain stations

Table 1a. Statistics for concentrations of dissolved and particulate substances at the upper Sacramento River station.

Measurement	Number of samples	Concentration				Coefficient of variation
		Mean	high	low	unit	
Sp. Conduct.	12	157	173	140	uS/cm	.06
Alkalinity	12	1.411	1.529	1.248	meq/L	.06
Nitrite	13	0.12	0.21	0.00	umol/L	.47
Nitrate	13	2.71	10.72	0.20	umol/L	1.29
Ammonium	13	0.65	1.11	0.30	umol/L	.42
Phosphate	13	0.69	0.97	0.33	umol/L	.31
D.Silica	13	385	428	329	umol/L	.08
SPM	13	14.8	25.1	8.6	mg/L	.31
P. Nitrogen	13	4.16	5.57	3.18	umol/L	.22
P. Carbon	13	38.5	50.7	28.4	umol/L	.18
T. Nitrogen	6	14.7	20.3	12.8	umol/L	.19
T. Phosphorus	6	1.17	1.32	0.99	umol/L	.12
D. Nitrogen	6	10.8	17.4	7.97	umol/L	.31
D. Phosphorus	6	0.84	1.02	0.53	umol/L	.22

Sp. Conduct. = Specific Conductance; SPM = suspended particulate matter
D = dissolved; P = Particulate; T = total

Table 1b. Statistics for transports of dissolved and particulate substances at the upper Sacramento River station.

Measurement	Number of samples	Transport				Coefficient of variation
		Mean	high	low	unit	
Flow rate	13	144	193	113	m^3/s	.19
Alkalinity	12	203.9	267.6	162.9	eq/s	.18
Nitrite	13	18.2	33.6	0.0	mmol/s	.49
Nitrate	13	411	1715	23.0	mmol/s	1.30
Ammonium	13	95.7	214	36.0	mmol/s	.51
Phosphate	13	101.	155	40.0	mmol/s	.38
D.Silica	13	55.6	75.4	37.2	mol/s	.21
SPM	13	2160	3530	972	g/s	.38
P. Nitrogen	13	583	706	423	mmol/s	.15
P. Carbon	13	5440	7180	3980	mmol/s	.16
T. Nitrogen	6	2090	2840	1560	mmol/s	.26
T. Phosphorus	6	165	196	121	mmol/s	.17
D. Nitrogen	6	1550	2430	972	mmol/s	.37
D. Phosphorus	6	119	149	65	mmol/s	.26

D = dissolved; SPM = suspended particulate matter; P = Particulate;
T = total

Table 2a. Statistics for concentrations of dissolved and particulate substances at the Colusa drain station

Measurement	Number of samples	Concentration				Coefficient of variation
		Mean	high	low	unit	
Sp. Conduct.	12	418	491	344	uS/cm	.10
Alkalinity	12	3.145	3.365	2.705	meq/L	.06
Nitrite	12	0.66	1.22	0.420	umol/L	.39
Nitrate	12	16.76	27.32	12.23	umol/L	.30
Ammonium	12	2.59	5.01	1.23	umol/L	.46
Phosphate	12	2.26	3.65	1.52	umol/L	.26
D.Silica	12	361	376	335	umol/L	.03
SPM	13	123.1	179.3	88.9	mg/L	.25
P. Nitrogen	13	14.9	22.0	12.3	umol/L	.17
P. Carbon	13	149	212	123	umol/L	.16
T. Nitrogen	6	46.7	55.2	40.6	umol/L	.14
T. Phosphorus	6	3.76	4.30	3.14	umol/L	.12
D. Nitrogen	6	38.0	46.3	30.4	umol/L	.17
D. Phosphorus	6	2.76	3.40	2.27	umol/L	.15

Sp. Conduct. = Specific Conductance; SPM = suspended particulate matter
D = dissolved; P = Particulate; T = total

Table 2b. Statistics for transports of dissolved and particulate substances at the Colusa drain station

Measurement	Number of samples	Transport				Coefficient of variation
		Mean	high	low	unit	
Flow rate	13	48	65	24	m^3/s	.27
Alkalinity	12	148	185	76.1	eq/s	.25
Nitrite	12	31	79.3	21	mmol/s	.11
Nitrate	12	716	1248	150	mmol/s	.26
Ammonium	12	112	150	65.2	mmol/s	.24
Phosphate	12	108	230	63.8	mmol/s	.44
D.Silica	12	17400	23500	8040	mol/s	.30
SPM	13	5710	8490	3060	g/s	.27
P. Nitrogen	13	701	884	357	mmol/s	.23
P. Carbon	13	7030	9200	3350	mmol/s	.24
T. Nitrogen	6	2330	3480	1530	mmol/s	.28
T. Phosphorus	6	188	271	120	mmol/s	.27
D. Nitrogen	6	1890	2810	1300	mmol/s	.29
D. Phosphorus	6	139	214	83	mmol/s	.32

D = dissolved; SPM = suspended particulate matter; P = Particulate;
T = total

Table 3a. Statistics for concentrations of dissolved and particulate substances at the Sutter drain station

Measurement	Number of samples	Concentration Mean	high	low	unit	Coefficient of variation
Sp. Conduct.	12	618	882	441	uS/cm	.27
Alkalinity	12	3.861	5.046	3.107	meq/L	.18
Nitrite	13	0.61	0.92	0.42	umol/L	.23
Nitrate	13	10.64	15.11	7.89	umol/L	.25
Ammonium	13	4.28	7.22	2.79	umol/L	.31
Phosphate	13	4.06	6.58	2.08	umol/L	.31
D.Silica	13	548	596	498	umol/L	.06
SPM	13	66.8	120	45.5	mg/L	.31
P. Nitrogen	13	12.0	19.5	8.7	umol/L	.24
P. Carbon	13	120	191	88	umol/L	.24
T. Nitrogen	6	36.8	44.5	29.5	umol/L	.15
T. Phosphorus	6	5.97	7.96	4.64	umol/L	.24
D. Nitrogen	6	27.6	31.8	24.6	umol/L	.10
D. Phosphorus	6	4.92	6.86	3.76	umol/L	.26

Sp. Conduct. = Specific Conductance; SPM = suspended particulate matter
D = dissolved; P = Particulate; T = total

Table 3b. Statistics for transports of dissolved and particulate substances at the Sutter drain station

Measurement	Number of samples	Transport Mean	high	low	unit	Coefficient of variation
Flow rate	13	49	64	23	m^3/s	.25
Alkalinity	12	182.6	260	101	eq/s	.27
Nitrite	13	28.9	42.8	16.4	mmol/s	.30
Nitrate	13	512	857	255	mmol/s	.36
Ammonium	13	203	367	111	mmol/s	.36
Phosphate	13	195	300	95	mmol/s	.38
D.Silica	13	26400	34300	13700	M/s	.25
SPM	13	3360	7460	1500	g/s	.51
P. Nitrogen	13	593	1210	296	mmol/s	.44
P. Carbon	13	5950	11800	2730	mmol/s	.44
T. Nitrogen	6	1940	2760	1280	mmol/s	.29
T. Phosphorus	6	308	421	241	mmol/s	.26
D. Nitrogen	6	1460	1970	939	mmol/s	.25
D. Phosphorus	6	253	357	205	mmol/s	.25

D = dissolved; SPM = suspended particulate matter; P = Particulate;
T = total

Table 4a. Statistics for concentrations of dissolved and particulate substances at the Feather River station

Measurement	Number of samples	Concentration				Coefficient of variation
		Mean	high	low	unit	
Sp. Conduct.	12	93	98	87	uS/cm	.04
Alkalinity	12	0.910	0.927	0.869	meq/L	.02
Nitrite	12	0.16	0.20	0.13	umol/L	.15
Nitrate	12	2.14	3.16	1.39	umol/L	.25
Ammonium	12	0.71	1.13	0.34	umol/L	.29
Phosphate	12	0.20	0.36	0.11	umol/L	.47
D.Silica	13	220	227	210	umol/L	.02
SPM	13	6.6	14.8	3.4	mg/L	.50
P. Nitrogen	13	1.03	1.24	0.76	umol/L	.16
P. Carbon	13	13.25	17.4	9.67	umol/L	.21
T. Nitrogen	6	11.28	13.29	9.73	umol/L	.10
T. Phosphorus	6	0.547	0.58	0.49	umol/L	.07
D. Nitrogen	6	10.32	11.91	9.19	umol/L	.09
D. Phosphorus	6	0.508	0.57	0.42	umol/L	.10

Sp. Conduct. = Specific Conductance; SPM = suspended particulate matter
D = dissolved; P = Particulate; T = total

Table 4b. Statistics for transports of dissolved and particulate substances at the Feather River station

Measurement	Number of samples	Transport				Coefficient of variation
		Mean	high	low	unit	
Flow rate	13	60.3	88	36	m^3/s	.23
Alkalinity	12	54.9	80.1	32.4	eq/s	.23
Nitrite	12	10.0	16.2	5.0	mmol/s	.32
Nitrate	12	130	214	65.5	mmol/s	.31
Ammonium	12	42	74	22.8	mmol/s	.32
Phosphate	12	11.8	22	6.5	mmol/s	.48
D.Silica	13	13200	19800	7850	mol/s	.23
SPM	13	400	748	184	g/s	.54
P. Nitrogen	13	62	101	34.6	mmol/s	.27
P. Carbon	13	804	1480	360	mmol/s	.34
T. Nitrogen	6	655	746	574	mmol/s	.10
T. Phosphorus	6	31.8	37.7	28.9	mmol/s	.11
D. Nitrogen	6	600	690	500	mmol/s	.11
D. Phosphorus	6	29.6	37.1	24.8	mmol/s	.15

D = dissolved; SPM = suspended particulate matter; P = Particulate;
T = total

Table 5a. Statistics for concentrations of dissolved and particulate substances at the lower Sacramento River station

Measurement	Number of samples	Concentration Mean	high	low	unit	Coefficient of variation
Sp. Conduct.	12	226	250	186	uS/cm	.08
Alkalinity	12	1.895	2.142	1.637	meq/L	.08
Nitrite	13	0.27	0.36	0.22	umol/L	.17
Nitrate	13	6.04	11.10	3.94	umol/L	.34
Ammonium	13	1.08	1.43	0.64	umol/L	.24
Phosphate	13	1.22	1.51	0.91	umol/L	.16
D.Silica	13	383	399	351	umol/L	.04
SPM	13	32.0	49.7	17.5	mg/L	.28
P. Nitrogen	13	5.70	7.40	4.09	umol/L	.18
P. Carbon	13	58.3	72.7	42.6	umol/L	.16
T. Nitrogen	6	24.1	30.6	20.9	umol/L	.16
T. Phosphorus	6	2.08	2.75	1.81	umol/L	.17
D. Nitrogen	6	18.71	25.3	14.6	umol/L	.20
D. Phosphorus	6	1.58	1.84	1.39	umol/L	.11

Sp. Conduct. = Specific Conductance; SPM = suspended particulate matter
D = dissolved; P = Particulate; T = total

Table 5b. Statistics for transports of dissolved and particulate substances at the lower Sacramento River station

Measurement	Number of samples	Transport Mean	high	low	unit	Coefficient of variation
Flow rate	13	301	378	195	m^3/s	.16
Alkalinity	12	570	714	342	eq/s	.16
Nitrite	13	83	136	46.8	mmol/s	.27
Nitrate	13	1860	3440	784	mmol/s	.44
Ammonium	13	329	484	148	mmol/s	.33
Phosphate	13	369	556	205	mmol/s	.26
D.Silica	13	115000	141000	68800	mol/s	.18
SPM	13	9800	18800	3550	g/s	.38
P. Nitrogen	13	1720	2370	934	mmol/s	.24
P. Carbon	13	17700	24200	8310	mmol/s	.24
T. Nitrogen	6	7380	9690	5250	mmol/s	.24
T. Phosphorus	6	634	853	486	mmol/s	.24
D. Nitrogen	6	5730	7840	3670	mmol/s	.27
D. Phosphorus	6	483	624	350	mmol/s	.21

D = dissolved; SPM = suspended particulate matter; P = Particulate;
T = total

and a 54 percent decrease in the combined flow at the upper Sacramento and Feather river stations. The totals of the transports from these four stations for the six dissolved inorganic substances measured in this study showed an mean decrease of 57 percent. This compares to the mean decrease in the transports of these substances at the lower Sacramento River station of 62 percent.

Total transports of elements such as phosphorus and nitrogen involve the transports of several chemical species. Relative importance of various chemical species in the transports of phosphorus and nitrogen was examined at the lower Sacramento River station (Table 5). Transport of DP was equivalent to 76 of the transport of TP, and the transport of DN was equivalent to 78 percent of the transport of TN. Therefore, assuming that particles were responsible for the differences between the total and dissolved transports, the particulate fraction (percentage) of the total transport was about the same for both phophorus and nitrogen (22 and 24 percent, respectively). This estimate of the transport of particulate nitrogen (22 percent) agreed with the result calculated from the independent PN analyses (23 percent).

At the lower Sacramento River station, the fraction of the transport of TP due to phosphate (58 percent) was almost twice the fraction of the transport of TN due to inorganic species (nitrate, nitrite, and ammonium; DIN; 31 percent). The differences between the transports of DP and phosphate and the transports of DN and DIN represented the dissolved organic fractions, if one assumes that relatively little dissolved organic phosphorus was reactive in the analysis for phosphate. Therefore, the dissolved organic fraction appeared larger for nitrogen than for phosphorus.

Transport of nitrate was equivalent to 82 percent of the transport of DIN, 32 percent of the transport of DN, and 25 percent of the transport of TN at the lower Sacramento River station.

Mean transports are shown in Table 6 to demonstrate the relative contribution of the tributary rivers and agricultural drains to transports at the lower Sacramento River station. Mean transports are expressed as percentage of the total of the transports from upper Sacramento River, Feather River, Colusa drain and Sutter drain stations (sources). Transports at the lower Sacramento River station are also shown relative to the total of the four sources in Table 6.

To facilitate description of the four sources (stations), the relative magnitude (percentage) of each source was ranked for each substance and property (except specific conductance). A single source was declared the major source when its magnitude was a least 30 percent higher than the magnitude of the second largest source. Major sources were identified for seven of the thirteen substances. An agricultural drain was the major source of six of these substances (Colusa: nitrate, SPM; Sutter: ammonium, phosphate, DP, and TP). Upper Sacramento River was the major source of dissolved silica. An agricultural drain was ranked highest for eleven of the thirteen substances (Colusa: SPM, nitrate, nitrite, DN, PN, TN, and PC; Sutter: phosphate, DP, TP, and ammonium), and Sutter drain was ranked second for the remaining two substances, alkalinity and dissolved silica, both of which were ranked first at the upper Sacramento River station. Upper Sacramento River,

Table 6. Comparison of major sources (as percentage of Total of Sources) of dissolved and particulate substances to the Sacramento River.

	Upper Sacramento River	+ Colusa Drain	+ Sutter Drain	+ Feather River	= Total of Sources	Lower Sacramento River
Alkalinity	35	25	31	9	100	97
Nitrite	21	35	33	11	100	94
Nitrate	23	41	29	7	100	105
Ammonium	21	25	45	9	100	73
Phosphate	24	26	47	3	100	89
D. Silica	49	15	24	12	100	102
D. Nitrogen	28	34	27	11	100	104
D. Phosphorus	22	26	47	5	100	89
SPM	19	49	29	3	100	84
P. Nitrogen	30	36	31	3	100	89
P. Carbon	28	37	31	4	100	92
T. Nitrogen	30	33	28	9	100	105
T. Phosphorus	24	27	44	5	100	92

D. = Dissolved; P. = Particulate; T. = Total;
SPM = Suspended Particulate Matter

Colusa drain, and Sutter drain were similar in the magnitudes of their transports for five substances (alkalinity, DN, PN, PC, and TN). The Feather River was ranked lowest (number four) for all of the substances. In fact, the Feather River amounted to less than half the transport of the third ranked source for all substances except dissolved silica.

Comparisons of the total transports from the rivers (Sacramento plus Feather Rivers) with the total transports from the drains (Sutter plus Colusa) showed that the total transports from the drains were over twice the total transports from the rivers for nine of the thirteen substances. The exceptions were alkalinity, dissolved silica, DP, and SPM. However, the total transport from the rivers was greater than the total transport from the drains in only one case, dissolved silica. An important task that is beyond the scope of this report is to model the daily concentration variability at the lower Sacramento River station as a function of transports from the four upstream stations. In lieu of this, mean transports at the lower Sacramento River station were compared to the sum of the mean transports from the four upstream sources in Table 6.

Mean transports at the lower Sacramento station ranged from 73 to 105 percent of the respective totals of the sources. Dissolved silica and alkalinity, which were the least variable in concentration at the four sources, showed mean transports at the lower Sacramento River station of 97 and 102 percent of the total of the sources, respectively, the closest values to 100 percent. This is particularly noteworthy because the Sacramento River was the major source of dissolved silica, whereas transport from the drains was higher than that from the rivers for alkalinity. Mean transport of ammonium was lowest (73 percent), but mean transports for nitrate, nitrite, dissolved nitrogen, and total nitrogen ranged from 94 to 105 percent. Mean transports for phosphate, dissolved phosphorus, and total phosphorus ranged from 89 to 92 percent. Mean transports for particulate substances, SPM, PN, and PC (84, 89, and 92 percent, respectively) at the lower Sacramento River station were consistently less than the corresponding totals of the sources.

Comparisons of transports at the lower Sacramento River station to the totals of the sources for nitrate, nitrite, ammonium, and dissolved nitrogen indicated a loss of ammonium and nitrite and a gain of nitrate and DN. The difference between the total and lower Sacramento River transports of nitrate was equivalent to 74 percent of difference in the transports of ammonium plus nitrite. The apparent gain of DN was many times larger in magnitude than this apparent loss of DIN.

Estimates of transports of PN were calculated from transports of TN and DN, assuming that PN equals TN minus DN. Concentrations of PN estimated in the same manner, were usually lower than measured concentrations of PN. Mean differences between the two PN values were equivalent to 6 percent of the mean of the measured PN at the upper Sacramento River and Feather River stations and 9 percent of the mean of the measured PN at the lower Sacramento River station. Much larger differences were observed at the two drain stations, where estimated concentrations of PN were consistently lower than measured concentrations. Mean differences between the two PN values were equivalent to 28 percent of the mean of the measured PN at the Sutter drain station and 32 percent of the mean of the measured PN at the

Colusa drain station. These results are consistent with the conclusion of Hager and Harmon (1984) that the largest differences between measured PN and estimated PN (TN-DN) occurred when SPM concentrations were highest, apparently because SPM interfered with the oxidation of PN. Mean concentrations of SPM ranged from 6.6 to 32 mg/L at the river stations, whereas mean concentrations were 66.8 mg/L at the Sutter drain station and 123.1 mg/L at the Colusa drain station.

Transports of PN calculated from estimated concentrations were lower than those calculated from measured concentrations, and a comparison of estimated mean transports from the four sources to mean transport at the lower Sacramento River station indicated a gain in PN over the reach (lower Sacramento River mean transport was 109 percent of the Total of Sources), a finding that is contrary to that for transports based on measured concentrations of PN.

We estimated transports of particulate phosphorus (PP) from measurements of TP and DP with the understanding that there might be differences between these estimates and transports based on measurements of PP, as was found for PN. The estimated mean transport of PP at the lower Sacramento River station was equivalent to 99 percent of the Total of Sources. The two drain stations were the largest sources, contributing 36 percent (Sutter drain station) and 32 percent (Colusa drain station) of the Total of Sources. The upper Sacramento River station contributed 30 percent. The Feather River station was lowest with a contribution of only 2 percent.

DISCUSSION OF RESULTS FROM THE FIVE STATIONS LOCATED UPSTREAM OF SACRAMENTO

Flows were measured at the upper Sacramento River, Colusa drain and Sutter drain stations, whereas flows were computed by difference at the Feather River and lower Sacramento River stations. Therefore, we could not test the accuracy of the flow budget or determine how errors in flow estimates affected the transport budget. Some properties of the concentration data, however, allowed us to evaluate the mean transport budget. We assumed that dissolved silica and alkalinity were conservative substances in this reach of the river, because effects of biological activity and chemical reactivity on concentrations of these substances probably were small. If this was the case and the estimated flow rates were reasonably accurate, the total of the mean transports of dissolved silica and alkalinity from the four sources should have been about the same as the transport at the lower Sacramento River station. However, if concentrations of these substances were the same at all the stations, we would not have been able to evaluate the transport balance because differences in transport among the stations would have been determined by the differences in flow, and the unknown flows were calculated by assuming a balance in flow among the stations. Fortunately, these substances exhibited less variation in concentration than most of the other substances at each station, but differences in mean concentration were large among the stations. Mean concentration for alkalinity varied by a factor of four among the stations, and that for dissolved silica varied by a factor of 2.5. In spite of these differences in concentration, the totals of the mean transports from the four sources for dissolved silica and alkalinity were equivalent to 102 percent and 97 percent of the respective mean transport at the lower Sacramento River station. Therefore, for these dissolved substances, which were probably well dispersed in the river, the transports nearly balanced.

Particulate substances probably settled in the water column by the time they reached the lower Sacramento River Station. Because we were able to sample only the surface water, it might be expected that mean transports for particulate substances at the lower Sacramento River station would be less than the sum of the mean transports at the four source stations. If estimates of PN and PP transports (based on total and dissolved fraction measurements) at the drain stations were low, as expected from the results of Hager and Harmon (1984), these results would also indicate a loss in this reach of the river.

Mean transport of ammonium at the lower Sacramento River station was lowest of all substances relative to the total of the mean transports at the four sources, indicating a loss, whereas transports of nitrate and TN were highest of all substances (105 percent), indicating a gain of nitrate and TN. The gain of nitrate was equivalent to about 75 percent of the loss of ammonium, but the gain of TN was much larger than the loss of ammonium, indicating a gain of dissolved organic nitrogen. The apparent gain of nitrate was equivalent to 0.32 umol/L. Assuming a mean travel time of 0.5 day for the reach of the Sacramento River between Knights Landing and the lower Sacramento River station, the rate of increase in nitrate concentration was 0.6 umol/L, which was about the same as that observed downstream of the input of municipal waste at Freeport.

The total of the flows at the drain stations averaged about one-half the total of the flows at the river stations, but the total of the transports at the drain stations exceeded the total of the transports at the river stations for all substances except dissolved silica. Evaporation accounts for some of the increase in concentrations as the diverted Sacramento River water travels through the Colusa and Sutter Basins, but other factors such as inputs of salts from rising subsurface waters in the Sutter Basin and dissolution of minerals in the Colusa Basin also cause increases in concentrations of some dissolved substances (Tanji and others, 1975; Tanji, 1981). Rising subsurface waters in the Sutter Basin account for some increases in both specific conductance and dissolved silica. High concentrations of suspended particles in the Colusa drain waters are associated with agricultural practices in the basin. Nitrogen fertilizers are applied in both basins, usually in the form of ammonium sulfate or dissolved ammonia, and high concentrations of ammonium and nitrate in the drain waters coincide with periods of application (Tanji and others, 1980).

Sutter and Colusa drain waters were generally higher in concentration of substances relative to the rivers, and some distinct differences existed between compositions of the drain waters from the two basins. These differences are related to many factors, some of which were mentioned above, including general geological features and irrigation practices in the basins (Tanji and others, 1975; Tanji, 1981). In addition to differences in composition between the two drain stations, our data showed that variations in concentration and flow occurred at each drain station over the period of the study. Large variations in concentrations and flow during the summer irrigation season have been attributed to variations in travel (residence) time of water within the basin and the draining of rice fields prior to harvest. Differences in the variability and compositions of drain waters among other agricultural basins in the central valley of California have shown the importance of these and other factors (California Regional Water Quality Control Board, 1979; Tanji, 1981).

SUMMARY AND CONCLUSIONS

Results of the Sacramento River transect study and the study of the sources upstream of Sacramento quantify major sources that can directly affect concentrations and transports of dissolved and particulate substances in the Sacramento River flow to San Francisco Bay. A significant factor affecting transport to San Francisco Bay is the major diversion of water at Walnut Grove, which directs flow southward to pumping plants that supply Federal and State water projects. The quantity of water diverted at Walnut Grove varies greatly, but averages about one-half the flow measured at Freeport. Major sources that affect concentrations of dissolved substances are located upstream of Walnut Grove. Consequently, the diversion at Walnut Grove greatly affects transports to San Francisco Bay, but does not directly affect concentrations in the Sacramento River. Biological processes and perhaps other transformations can affect concentrations of dissolved and particulate substances in the reach of the Sacramento River downstream of Freeport and Walnut Grove. Variations in flow of the river, which are caused by diversions, affect concentrations of dissolved and particulate substances in the water entering San Francisco Bay by diluting inputs and by influencing travel time to the estuary. This in turn directly affects the extent to which concentrations of reactive substances are changed. Therefore, variability in the concentrations and transports of dissolved and particulate substances in the Sacramento River flow to San Francisco Bay results from many factors. These include the relative rates of supply of water and substances from many sources, various transformations in the river, and withdrawals for agricultural and other uses.

As shown in previous studies (California Department of Water Resources, 1962), concentrations of substances in the Sacramento River are changed by mixing with various inflows. Municipal waste inflow at Freeport caused an increase in concentration and transport of phosphate and ammonium in the river. From the large changes in concentration observed in the river, this source appeared to be the major source of phosphate and ammonium. As a consequence of nitrification, municipal waste inflow could also affect concentrations of nitrate and nitrite at downstream locations. Inputs of nitrate and nitrite from agricultural drains are also important, but to a lesser degree. Specific conductance, alkalinity, and concentrations of dissolved silica in the river were not affected by the inflow of municipal waste at Freeport.

In general, lowest concentrations of dissolved and particulate substances measured in this study were found in the Feather and American Rivers. Therefore, increases in flows from these two tributaries relative to the other major inflows will result in lower concentrations of these substances in the Sacramento River flow to San Francisco Bay.

Concentrations measured in the American River were lower than those measured in the Feather River for most substances, indicating that the American River flow has the greater potential for changing concentrations by dilution.

Inflows from agricultural drains increased specific conductance and alkalinity, but decreased concentrations of dissolved silica. Inflows from the Feather River and American River also resulted in decreases in concentrations of dissolved silica. Concentrations of particulate substances, SPM, PC, and PN, were increased by inflows from the agricultural drains and, in general, decreased by the tributary river inflows. Concentrations of particulate substances were lower at Freeport than at upstream locations, but were higher at locations downstream of the input of municipal waste.

The large, late-summer decrease in flow from the drains that was observed in this study was a major factor reducing the transport of dissolved and particulate substances in the Sacramento River upstream of Sacramento. In addition, some moderate to major changes in concentrations (largely decreases) coincided with the event. Flow of the American River typically increases during late summer and early fall as water is released from upstream reserviors for fisheries needs. As a consequence, concentrations of some substances in the Sacramento River downstream of Sacramento are more dilute, and transports can reach lowest annual rates (Schemel and Hager, 1986). A key point is that changes occur over short periods of time, and that changes in transports and concentrations can be large. Results from previous studies (Schemel, Harmon, Hager, and Peterson, 1984; Schemel and Hager, 1986) indicate that these variations in the Sacramento River affect abundances and distributions of some substances in San Francisco Bay.

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APPENDIX

Table A-1. Concentrations of dissolved and particulate substances at the upper Sacramento River station during August and September of 1985.

DAY OF YEAR	SPEC. COND. uS/cm	ALKALIN. meq/L	NO_2^- umol/L	NO_3^- umol/L	NH_4^+ umol/L	PO_4^{3-} umol/L	SiO_2 umol/L	S. PART. MATTER mg/L
220	140	1.529	0.08	1.14	0.53	0.74	394	18.8
231	149	1.324	0.13	1.40	1.11	0.66	361	18.3
234	156	1.421	0.13	1.30	0.76	0.69	428	15.3
239	166	1.499	0.15	0.74	0.96	0.61	417	14.4
242	173	1.518	0.08	1.01	0.95	0.96	394	25.1
246	*	*	0.11	1.22	0.64	0.82	400	17.8
249	161	1.444	0.15	0.67	0.73	0.48	411	9.5
253	150	1.372	0.11	3.64	0.51	0.76	403	12.3
256	151	1.248	0.21	10.72	0.89	0.97	392	16.4
259	159	1.362	0.21	9.77	0.38	0.96	371	14.5
262	161	1.415	0.18	3.13	0.39	0.66	368	10.5
266	148	1.335	0.00	0.30	0.30	0.33	336	11.2
269	168	1.468	0.08	0.20	0.32	0.36	329	8.6

DAY OF YEAR	TOTAL N	DISSOL. N	TOTAL P	DISSOL. P	PART. C	PART. N	ESTIMATED FLOW
	umol/L						m^3/s
220	*	*	*	*	32.2	3.35	175.0
231	*	*	*	*	37.2	3.66	193.0
234	13.33	9.67	1.27	0.97	41.3	4.03	154.0
239	13.71	9.57	1.23	0.91	43.8	4.54	117.0
242	*	*	*	*	50.7	5.57	119.0
246	13.91	9.39	1.22	0.91	35.0	3.71	131.0
249	*	*	*	*	29.9	3.18	133.0
253	14.24	10.98	0.99	0.71	28.4	3.26	187.0
256	*	*	*	*	34.8	3.30	160.0
259	20.28	17.37	1.32	1.02	35.1	3.62	140.0
262	*	*	*	*	41.2	5.21	128.0
266	12.81	7.97	0.99	0.53	50.2	5.57	122.0
269	*	*	*	*	41.0	5.03	113.0

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* = DATA NOT AVAILABLE

SPEC. COND = Specific Conductance; ALKALIN. = Alkalinity; S. PART. Matter = Suspended Particulate Matter; DISSOL. = Dissolved; PART. = Particulate

Table A-2. Concentrations of dissolved and particulate substances at the Feather River station during August and September of 1985.

DAY OF YEAR	SPEC. COND. uS/cm	ALKALIN. meq/L	NO_2^- umol/L	NO_3^- umol/L	NH_4^+ umol/L	PO_4^{3-} umol/L	SiO_2 umol/L	S. PART. MATTER mg/L
220	87	0.869	0.20	1.39	0.41	0.13	210	8.8
231	90	0.894	0.20	1.45	0.78	0.33	214	11.5
234	91	0.921	0.14	1.75	0.80	0.36	216	3.4
239	92	0.912	0.17	2.15	1.13	0.34	216	5.7
242	91	0.911	0.19	2.38	0.87	0.14	221	14.8
246	*	*	0.16	2.77	0.71	0.14	226	6.0
249	93	0.927	*	*	*	*	222	5.0
253	97	0.923	0.13	3.16	0.79	0.17	227	5.3
256	98	0.917	0.16	2.43	0.61	0.11	225	6.7
259	97	0.921	0.15	2.48	0.64	0.18	225	4.0
262	96	0.917	0.15	2.22	0.66	0.17	219	4.7
266	94	0.906	0.15	1.70	0.34	0.11	220	3.6
269	93	0.900	0.14	1.82	0.72	0.18	218	6.0

DAY OF YEAR	TOTAL N	DISSOL. N	TOTAL P	DISSOL. P	PART. C	PART. N	ESTIMATED FLOW
	umol/L						m^3/s
220	*	*	*	*	11.6	0.92	81.0
231	*	*	*	*	9.7	0.82	65.0
234	10.75	9.89	0.55	0.53	10.2	0.76	54.0
239	11.47	10.58	0.58	0.57	11.5	0.90	65.0
242	*	*	*	*	17.4	1.23	50.0
246	11.39	10.63	0.49	0.42	15.5	1.24	59.0
249	*	*	*	*	14.8	1.08	48.0
253	13.29	11.91	0.56	0.51	15.3	1.24	53.0
256	*	*	*	*	16.8	1.15	88.0
259	11.04	9.69	0.58	0.54	12.4	1.02	52.0
262	*	*	*	*	15.8	1.13	66.0
266	9.73	9.19	0.52	0.48	11.3	0.95	67.0
269	*	*	*	*	10.0	0.96	36.0

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* = DATA NOT AVAILABLE
SPEC. COND = Specific Conductance; ALKALIN. = Alkalinity; S. PART. Matter = Suspended Particulate Matter; DISSOL. = Dissolved; PART. = Particulate

Table A-3. Concentrations of dissolved and particulate substances at the lower Sacramento River station during August and September of 1985.

DAY OF YEAR	SPEC. COND. uS/cm	ALKALIN. meq/L	NO_2^- umol/L	NO_3^- umol/L	NH_4^+ umol/L	PO_4^{3-} umol/L	SiO_2 umol/L	S. PART. MATTER mg/L
220	186	1.637	0.22	3.94	0.90	0.91	376	32.2
231	223	1.733	0.22	5.87	1.24	0.96	396	17.5
234	219	1.901	0.25	4.26	1.14	1.15	397	29.1
239	237	2.041	0.24	5.07	1.27	1.19	395	36.5
242	250	2.142	0.34	5.49	1.43	1.51	393	39.5
246	*	*	0.26	5.45	0.64	1.16	395	31.9
249	231	2.012	0.24	5.10	1.26	1.24	399	30.5
253	231	1.957	0.31	7.86	1.31	1.46	387	37.1
256	212	1.746	0.36	8.57	1.28	1.47	374	49.7
259	234	1.913	0.28	11.10	1.02	1.38	376	24.5
262	249	2.035	0.33	7.02	1.05	1.27	380	41.1
266	229	1.872	0.27	4.79	0.67	1.07	351	27.8
269	210	1.756	0.24	4.02	0.76	1.05	353	18.2

DAY OF YEAR	TOTAL N	DISSOL. N	TOTAL P	DISSOL. P	PART. C	PART. N	ESTIMATED FLOW
	umol/L						m^3/s
220	*	*	*	*	54.5	5.11	321.0
231	*	*	*	*	43.9	4.09	342.0
234	21.04	16.79	1.86	1.50	51.8	4.64	314.0
239	23.49	18.65	1.94	1.59	61.3	5.42	283.0
242	*	*	*	*	65.8	6.14	271.0
246	22.11	17.12	1.81	1.45	52.7	5.01	297.0
249	*	*	*	*	53.6	5.17	294.0
253	26.55	19.85	2.18	1.71	66.4	6.50	365.0
256	*	*	*	*	64.0	5.75	378.0
259	30.62	25.30	2.75	1.84	72.7	7.23	310.0
262	*	*	*	*	67.9	7.40	290.0
266	20.85	14.55	1.93	1.39	60.4	6.89	252.0
269	*	*	*	*	42.6	4.79	195.0

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* = DATA NOT AVAILABLE
SPEC. COND = Specific Conductance; ALKALIN. = Alkalinity; S. PART. Matter = Suspended Particulate Matter; DISSOL. = Dissolved; PART. = Particulate

Table A-4. Concentrations of dissolved and particulate substances at the Sutter drain station during August and September of 1985.

DAY OF YEAR	SPEC. COND. uS/cm	ALKALIN. meq/L	NO_2^- umol/L	NO_3^- umol/L	NH_4^+ umol/L	PO_4^{3-} umol/L	SiO_2 umol/L	S. PART. MATTER mg/L
220	483	3.259	0.53	8.24	3.57	3.30	524	48.5
231	468	3.276	0.67	7.89	3.34	3.53	520	45.5
234	441	3.107	0.48	8.46	3.33	2.08	498	50.9
239	489	3.394	0.48	9.19	2.79	3.23	543	58.8
242	531	3.492	0.47	8.04	3.39	3.18	544	57.8
246	*	*	0.51	8.67	3.48	3.67	544	56.2
249	552	3.558	0.42	8.82	3.70	3.15	543	58.5
253	526	3.406	0.69	11.72	3.75	4.25	512	120.3
256	607	3.738	0.66	11.70	4.67	4.44	536	85.1
259	756	4.476	0.73	14.78	6.33	5.12	590	81.5
262	805	4.725	0.70	13.83	5.66	6.12	594	82.6
266	872	4.853	0.67	11.86	4.39	6.58	574	58.1
269	882	5.046	0.92	15.11	7.22	4.13	596	65.0

DAY OF YEAR	TOTAL N	DISSOL. N	TOTAL P	DISSOL. P	PART. C	PART. N	ESTIMATED FLOW
	umol/L						m^3/s
220	*	*	*	*	108.0	10.01	31.0
231	*	*	*	*	98.5	9.65	42.0
234	35.89	25.23	4.65	3.76	114.1	11.16	55.0
239	29.46	26.73	4.64	3.95	88.1	9.36	52.0
242	*	*	*	*	89.8	8.71	52.0
246	32.40	24.64	4.84	4.01	109.9	10.96	52.0
249	*	*	*	*	106.7	10.63	55.0
253	44.47	31.79	6.48	4.80	190.9	19.45	62.0
256	*	*	*	*	145.9	14.22	64.0
259	41.82	30.45	7.25	6.16	143.9	14.03	58.0
262	*	*	*	*	139.8	13.62	49.0
266	36.65	26.82	7.96	6.86	104.9	11.22	35.0
269	*	*	*	*	118.5	12.89	23.0

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* = DATA NOT AVAILABLE
SPEC. COND = Specific Conductance; ALKALIN. = Alkalinity; S. PART. Matter = Suspended Particulate Matter; DISSOL. = Dissolved; PART. = Particulate

Table A-5. Concentrations of dissolved and particulate substances at the Colusa drain station during August and September of 1985.

DAY OF YEAR	SPEC. COND. uS/cm	ALKALIN. meq/L	NO_2^- umol/L	NO_3^- umol/L	NH_4^+ umol/L	PO_4^{3-} umol/L	SiO_2 umol/L	S. PART. MATTER mg/L
220	411	3.226	0.64	15.42	2.86	2.12	357	120.2
231	444	3.251	0.55	16.42	2.29	1.52	353	118.5
234	406	3.209	*	*	*	*	*	125.6
239	407	3.227	0.44	12.52	2.22	1.81	365	173.3
242	400	3.193	0.42	12.71	1.79	2.00	369	165.0
246	*	*	0.42	12.23	1.23	1.70	373	101.4
249	395	3.136	0.54	15.39	2.49	1.78	376	90.9
253	368	2.823	0.65	29.81	1.29	3.65	368	88.9
256	344	2.705	1.22	12.29	2.10	2.40	361	111.8
259	416	3.087	0.53	13.90	2.00	2.31	367	92.3
262	460	3.365	0.60	18.58	3.12	2.35	364	105.4
266	491	3.349	0.94	27.32	4.68	2.58	349	179.3
269	468	3.171	1.01	24.57	5.01	2.87	335	127.5

DAY OF YEAR	TOTAL N	DISSOL. N	TOTAL P	DISSOL. P	PART. C	PART. N	ESTIMATED FLOW
	umol/L						m^3/s
220	*	*	*	*	129.5	13.71	34.0
231	*	*	*	*	145.5	14.10	42.0
234	41.52	34.80	3.59	2.56	156.2	15.66	50.0
239	43.70	30.41	3.57	2.50	168.6	16.54	49.0
242	*	*	*	*	169.8	16.57	50.0
246	40.57	33.86	3.14	2.27	152.9	16.12	53.0
249	*	*	*	*	123.1	12.25	59.0
253	55.24	44.59	4.30	3.40	127.6	13.46	63.0
256	*	*	*	*	141.5	13.60	65.0
259	44.25	37.76	3.68	2.82	129.6	12.50	59.0
262	*	*	*	*	140.1	12.68	48.0
266	54.73	46.32	4.28	2.98	211.9	21.97	28.0
269	*	*	*	*	139.5	14.87	24.0

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* = DATA NOT AVAILABLE
SPEC. COND = Specific Conductance; ALKALIN. = Alkalinity; S. PART. Matter = Suspended Particulate Matter; DISSOL. = Dissolved; PART. = Particulate

Table A-6. Concentrations of dissolved and particulate substances at selected locations in the reach of the Sacramento River between Knights Landing (station 1) and Rio Vista (station 12) on August 27, 1985.

STATION	TIME	RIVER MILE	SPEC. COND. uS/cm	ALKALIN. meq/L	NO_2^- umol/L	NO_3^- umol/L	NH_4^+ umol/L
1	740	91.0	167	1.455	0.02	0.54	0.49
2	840	82.6	222	1.873	0.10	3.51	0.95
3	900	80.0	98	0.934	0.02	2.22	0.55
4	940	72.5	213	1.843	0.02	4.44	0.81
5	1015	62.6	*	*	*	*	*
6	1035	60.4	55	0.448	0.00	0.37	0.81
7	1100	58.4	188	1.612	0.05	3.65	1.29
8	1125	47.9	185	1.582	0.10	3.99	1.44
9	1145	42.4	187	1.570	0.10	4.56	12.44
10	1215	34.6	184	1.528	0.23	5.90	7.55
11	1245	27.5	187	1.560	0.25	5.63	5.99
12	1310	20.6	187	1.558	0.28	6.50	4.53

STATION	TIME	RIVER MILE	PO_4^{3-} umol/L	SiO_2 umol/L	S. PART. MATTER mg/L	PART. C umol/L	PART. N umol/L
1	740	91.0	0.88	413	25.7	52.3	6.14
2	840	82.6	1.16	379	35.9	80.5	8.32
3	900	80.0	0.60	214	6.9	12.8	1.11
4	940	72.5	1.22	351	42.2	60.2	5.53
5	1015	62.6	*	*	*	*	*
6	1035	60.4	0.21	155	6.1	27.1	2.27
7	1100	58.4	1.12	328	38.2	47.4	5.00
8	1125	47.9	1.31	327	18.7	37.9	3.68
9	1145	42.4	4.25	334	21.8	41.4	4.28
10	1215	34.6	4.38	335	27.8	50.2	4.33
11	1245	27.5	4.72	334	32.0	55.8	5.10
12	1310	20.6	3.88	338	16.9	28.0	2.82

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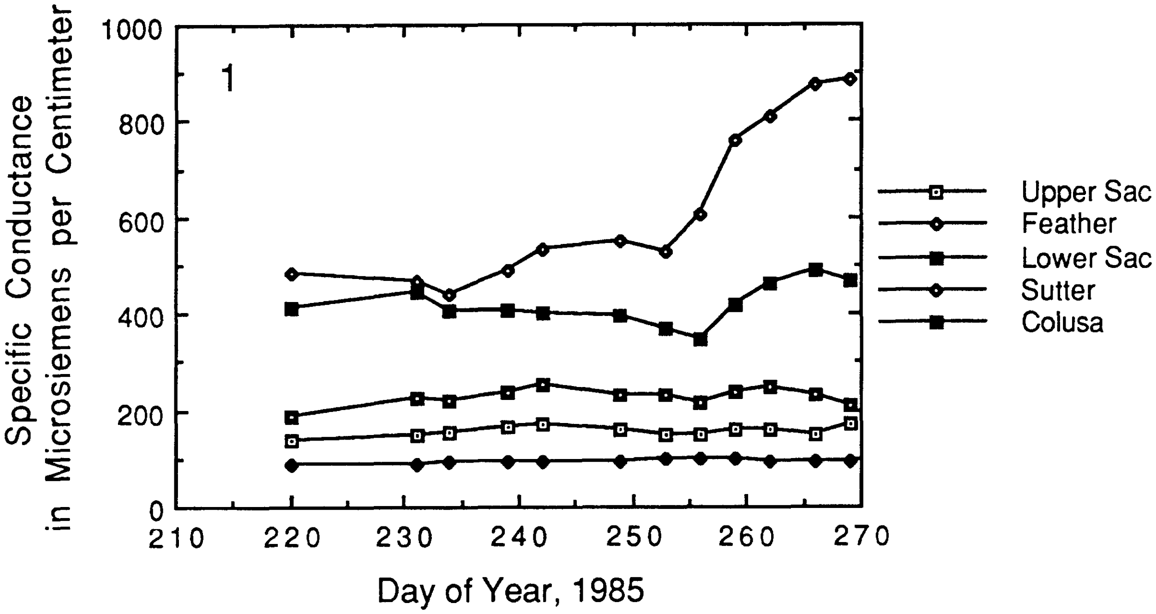
* = DATA NOT AVAILABLE
SPEC. COND. = Specific Conductance; ALKALIN. = Alkalinity;
S. PART. Matter = Suspended Particulate Matter; PART. = Particulate

Figure A. Measurements of properties, dissolved and particulate nutrient concentrations and suspended particulate concentrations at five station locations: upper Sacramento River, Feather River, lower Sacramento River, Sutter drain, and Colusa drain. Measurements are: (1) specific conductance in microsiemens per centimeter, (2) alkalinity in milliequivlents per liter, (3) dissolved silica in micromoles per liter, (4) dissolved reactive phosphate in micromoles per liter, (5) nitrate in micromoles per liter, (6) nitrite in micromoles per liter, (7) ammonium in micromoles per liter, (8) particulate nitrogen in micromoles per liter, (9) suspended particulate matter in milligrams per liter, (10) particulate carbon in micromoles per liter, (11) total nitrogen in micromoles per liter, (12) dissolved nitrogen in micromoles per liter, (13) total phosphorus in micromoles per liter, and (14) dissolved phosphorus in micromoles per liter.



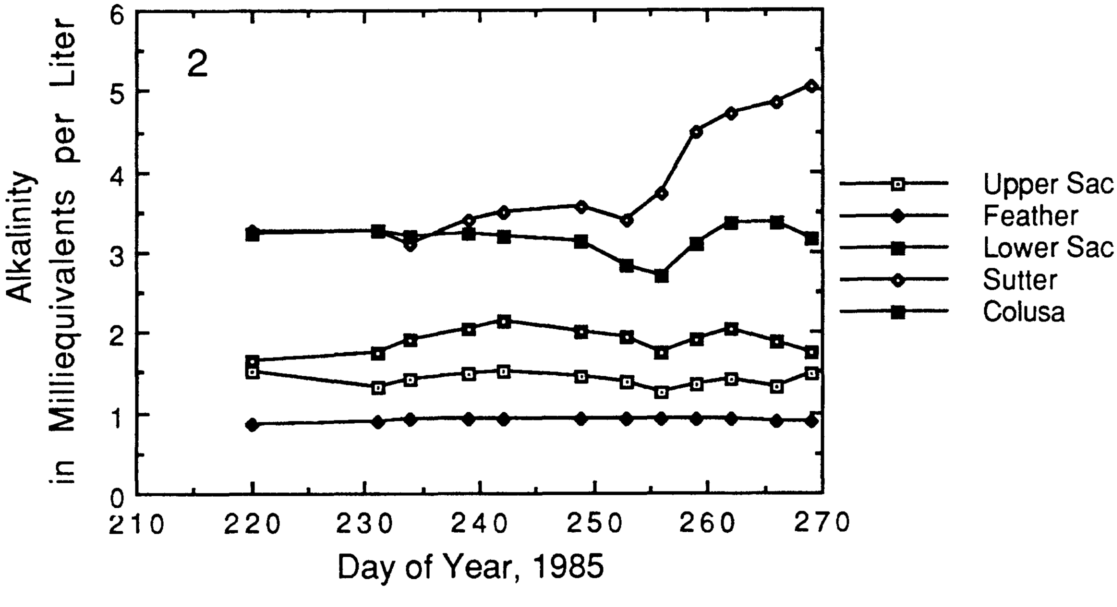
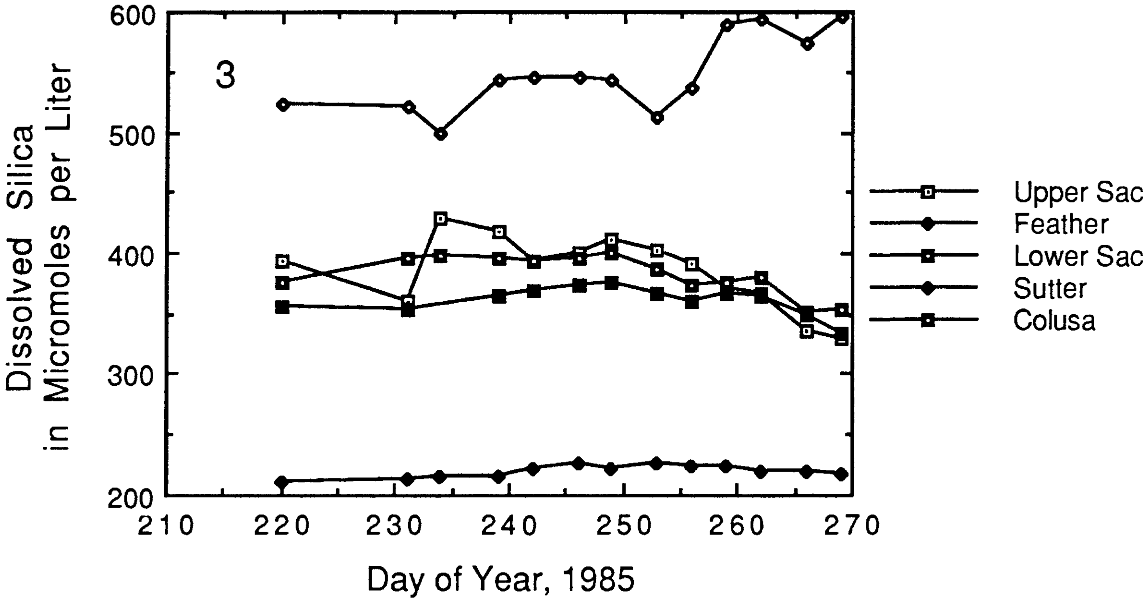


Figure A.-- continued.



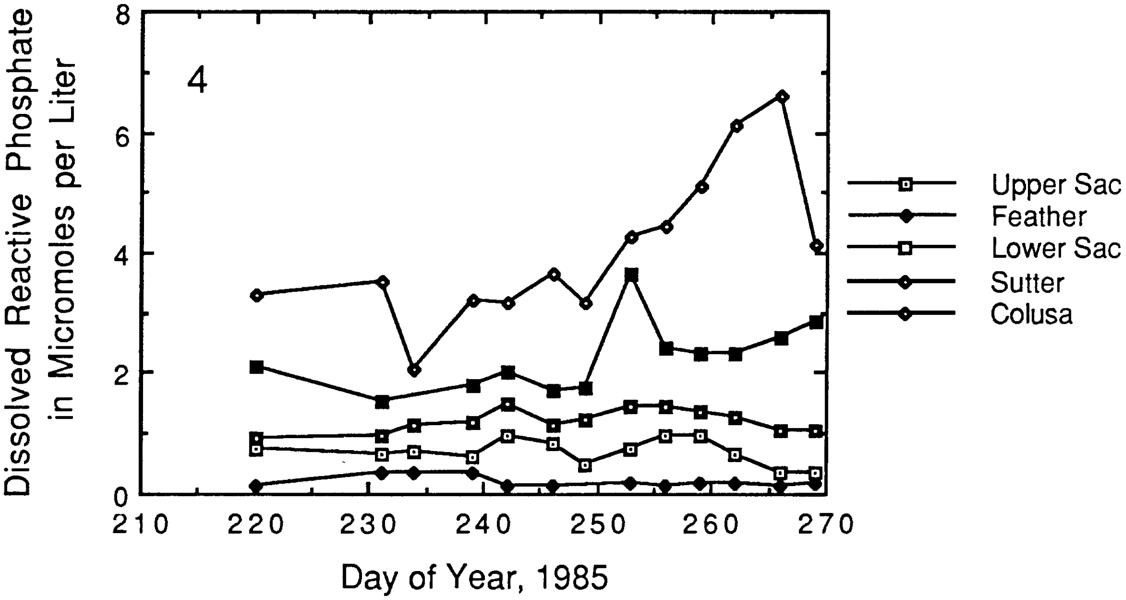
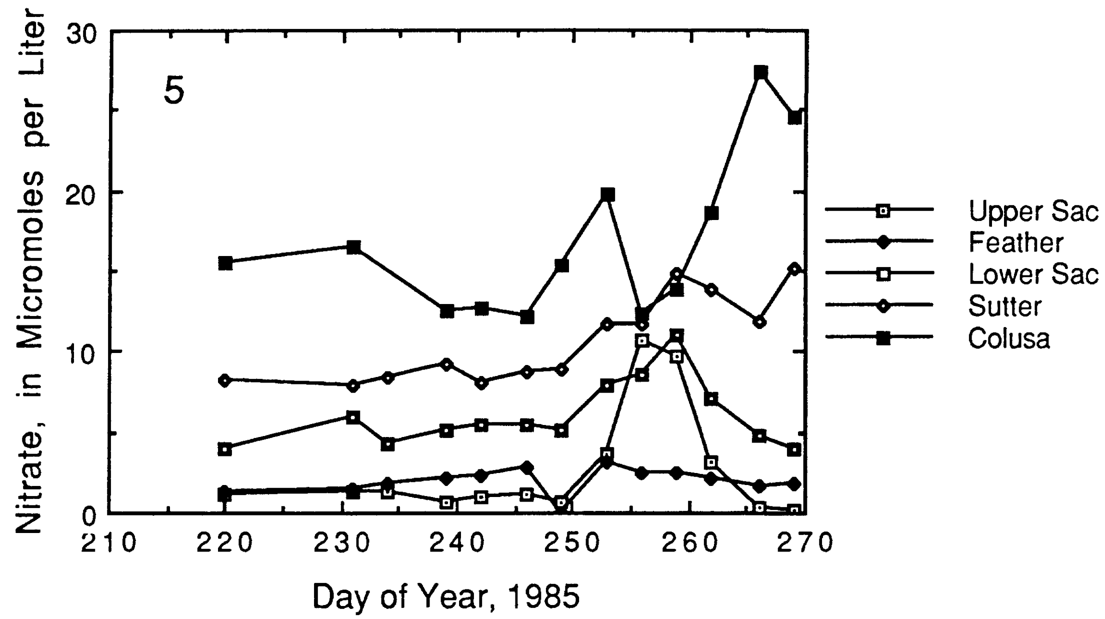


Figure A.-- continued.



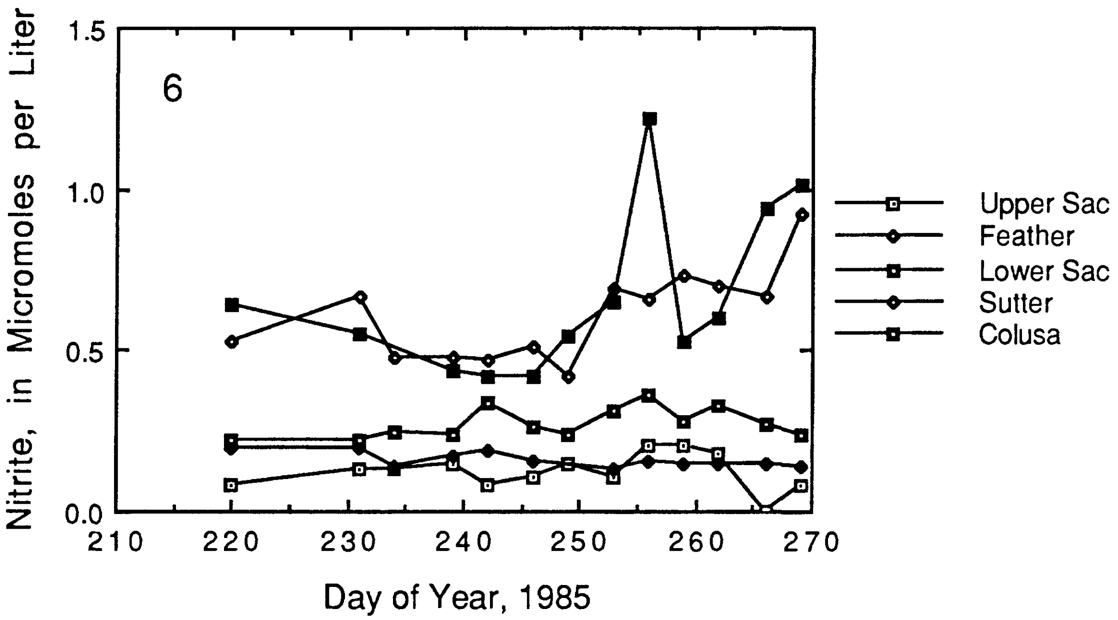
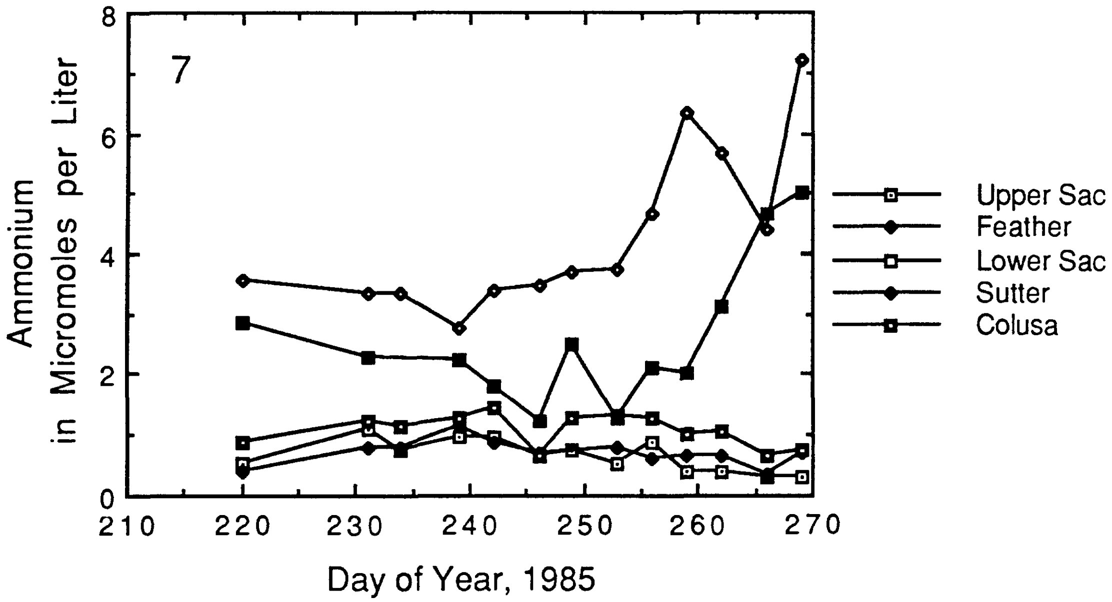
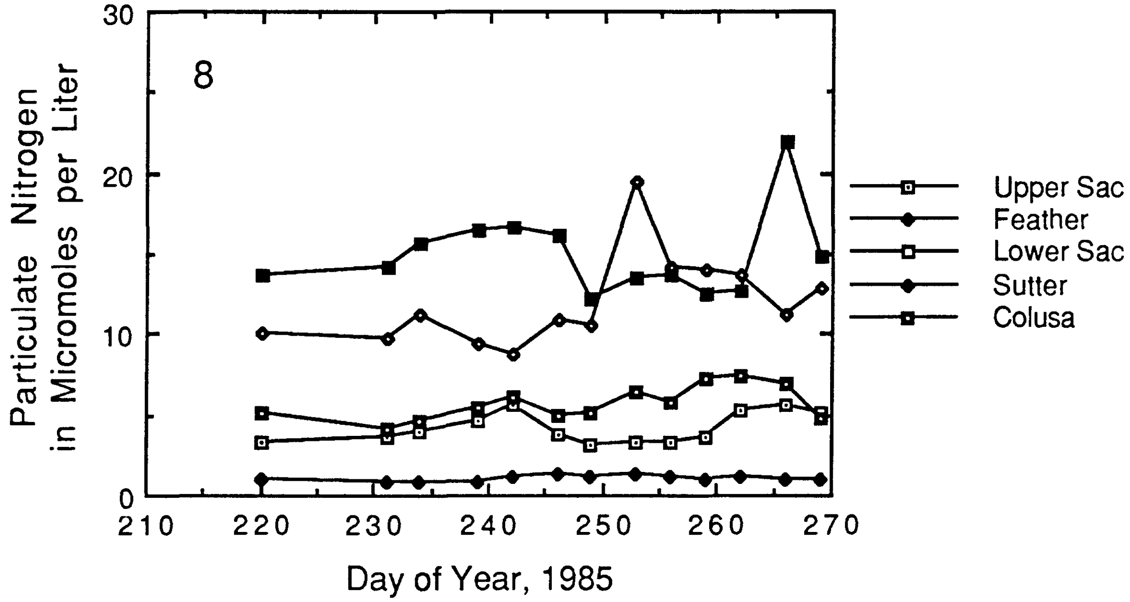


Figure A.-- continued.





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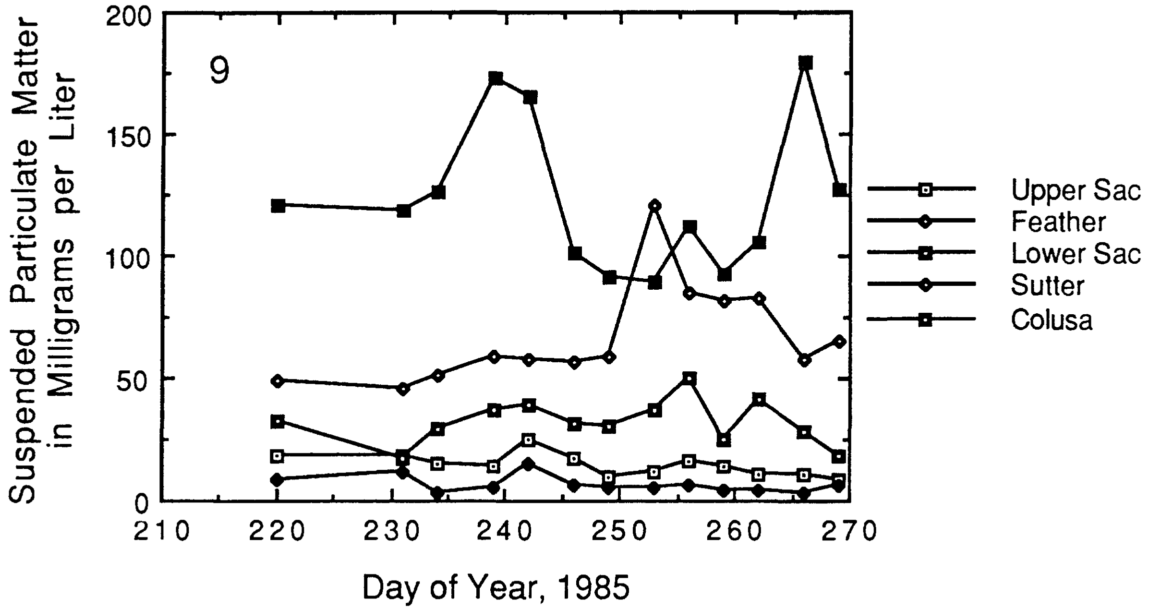

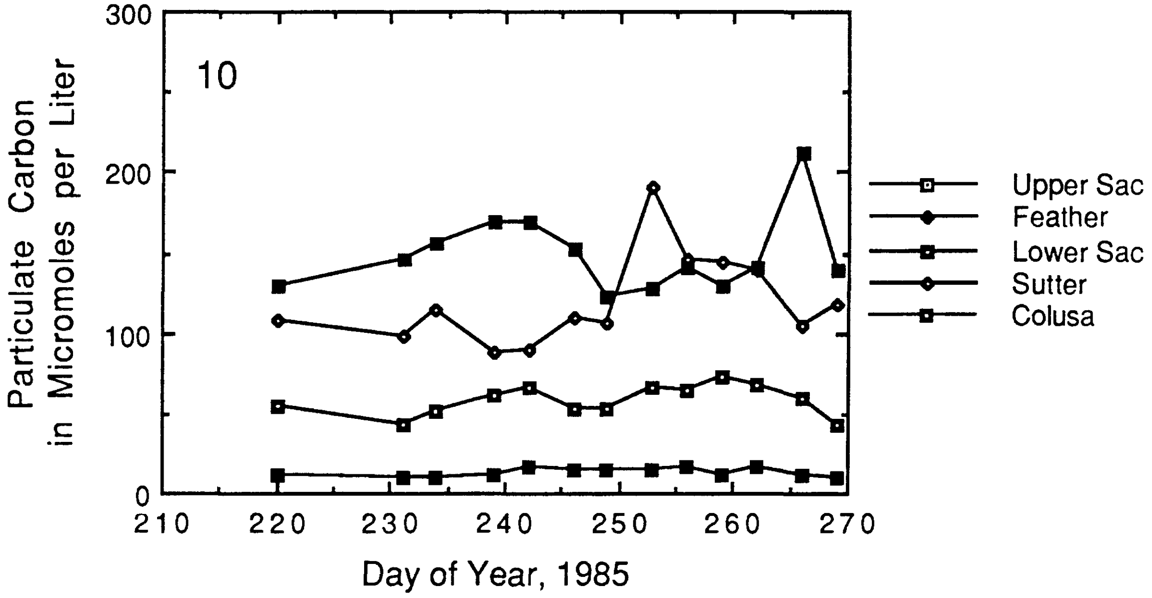

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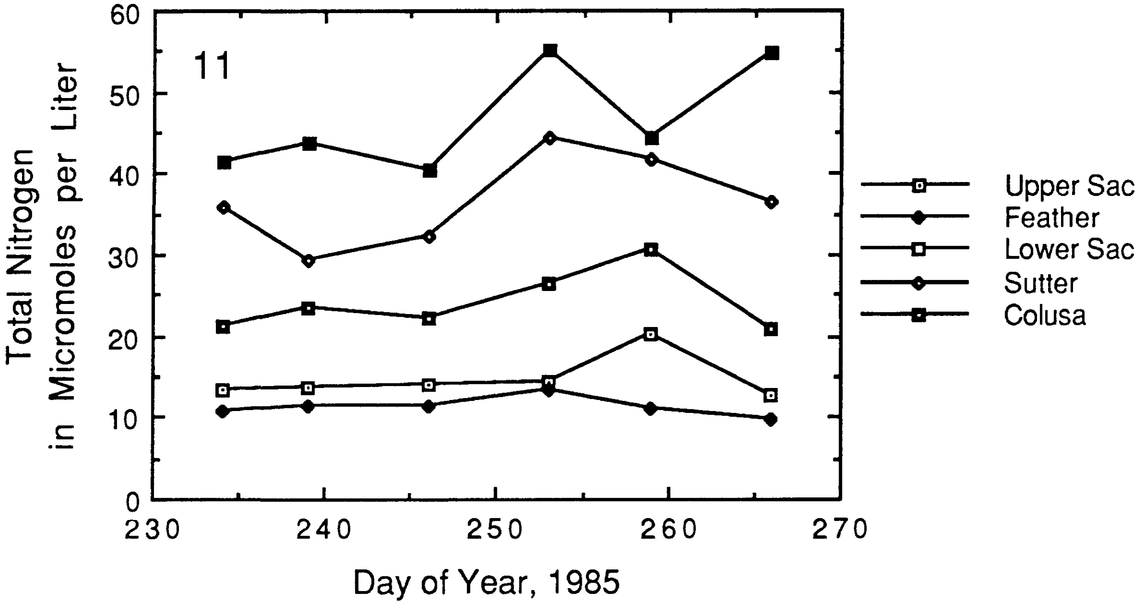


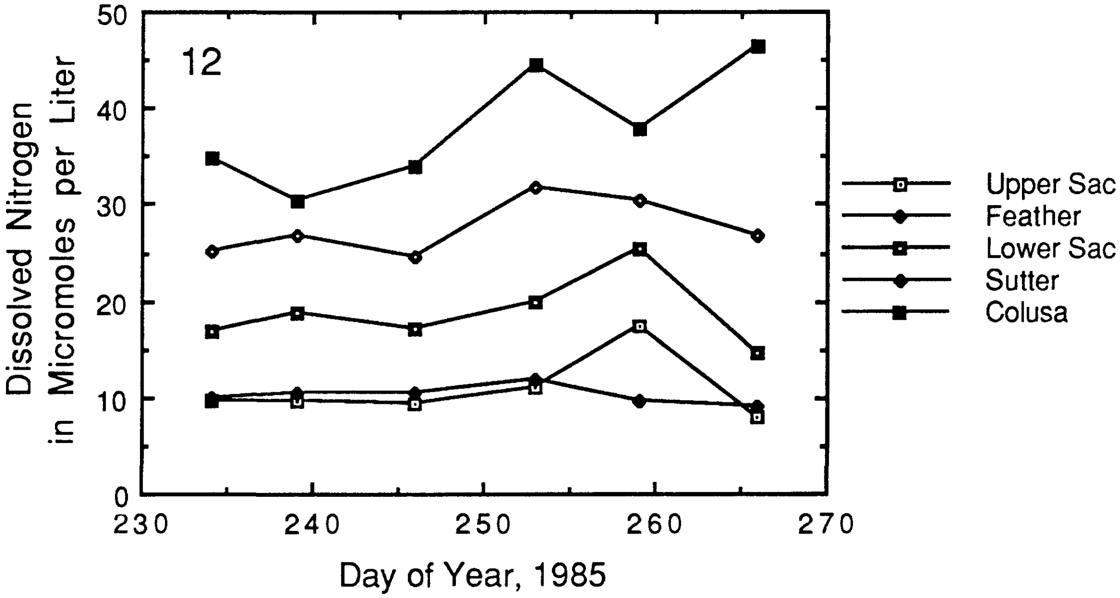
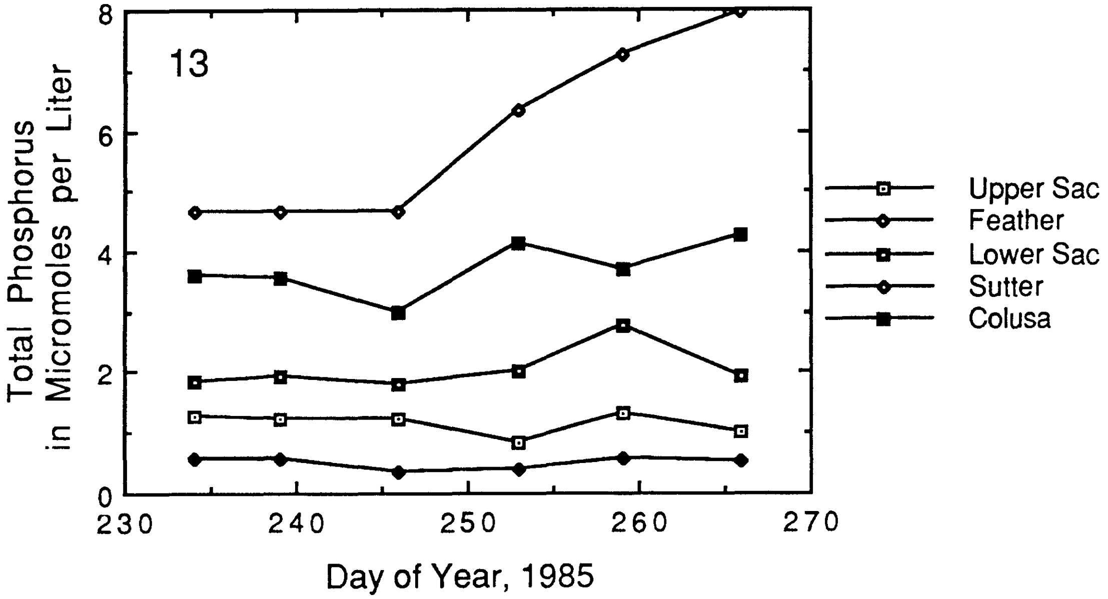


Figure A.-- continued.



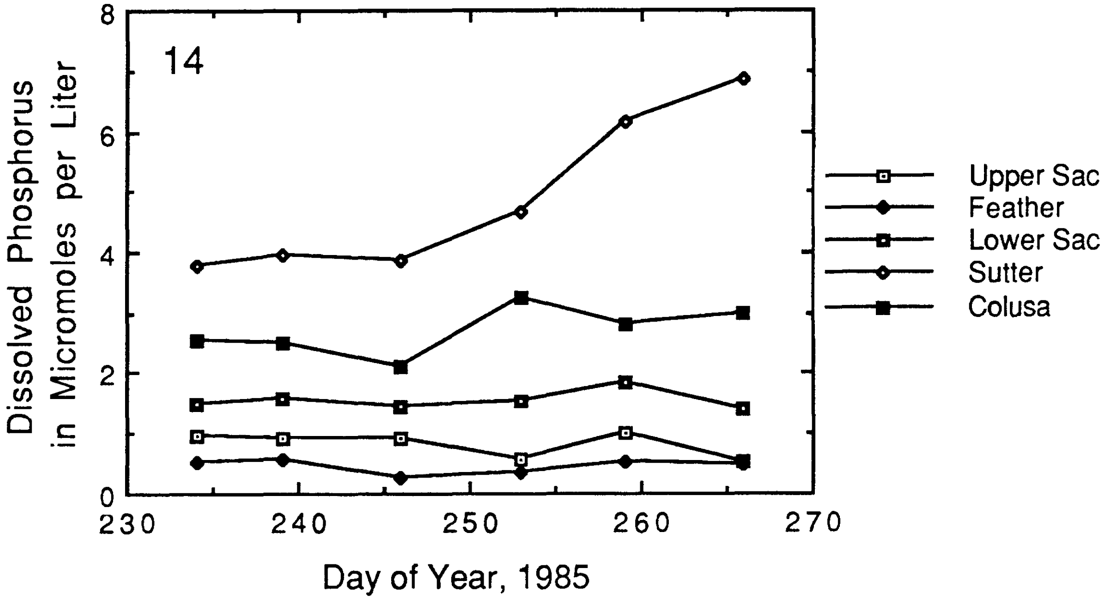


Figure A.-- continued.

Figure B. Transports of dissolved and particulate nutrients, and suspended particulate matter at five station locations: Upper Sacramento River, Feather River, Lower Sacramento River, Sutter drain, and Colusa drain. Transports include (1) alkalinity in equivalents per second, (2) dissolved reactive phosphate in millimoles per second, (3) dissolved silica in moles per second, (5) nitrite in millimoles per second, (6) ammonium in millimoles per second, (8) particulate carbon in moles per second, (9) suspended particulate matter in kilograms per second, (10) total nitrogen in moles per second, (11) dissolved nitrogen in moles per second, (12) total phosphorus in millimoles per second, and (13) dissolved phosphorus in millimoles per second.

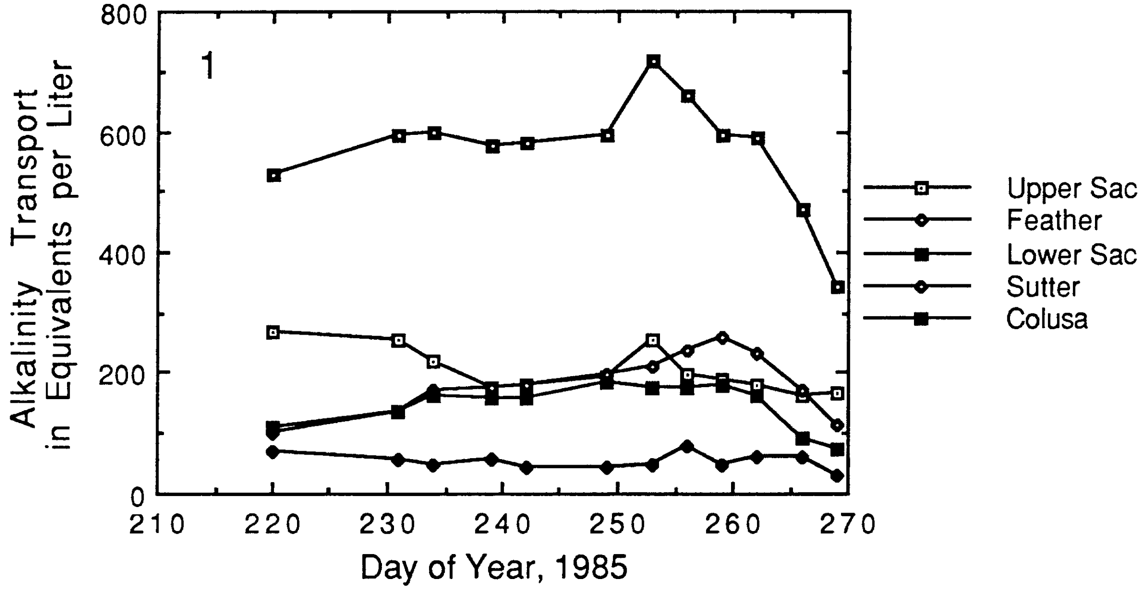
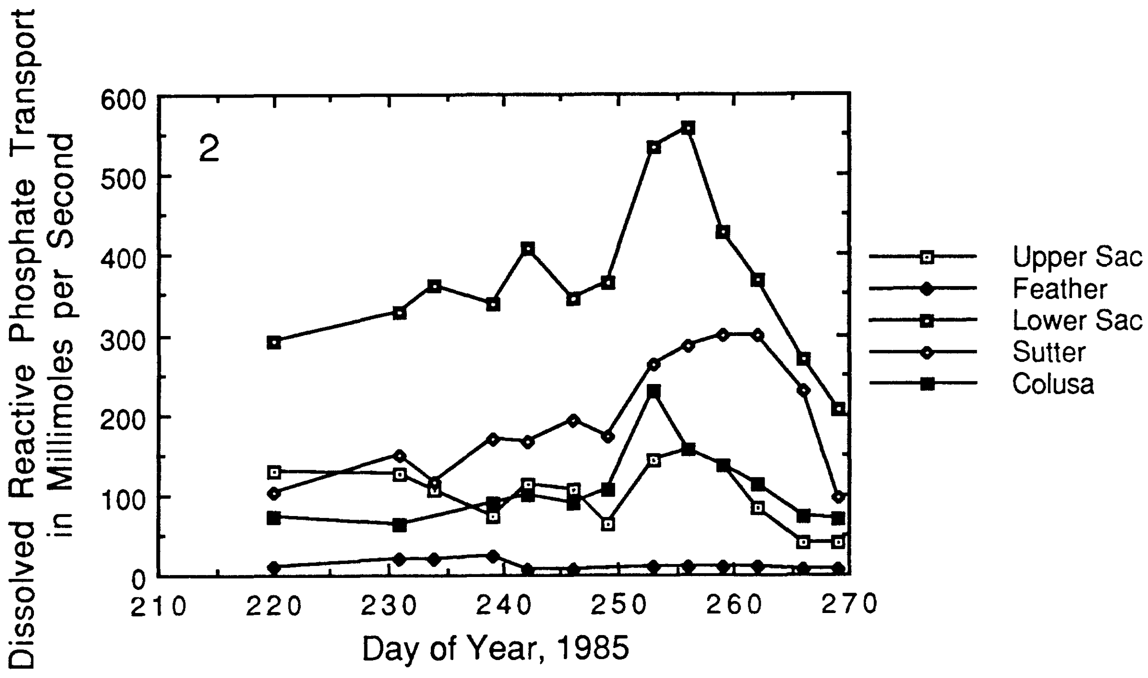


Figure B.-- continued.



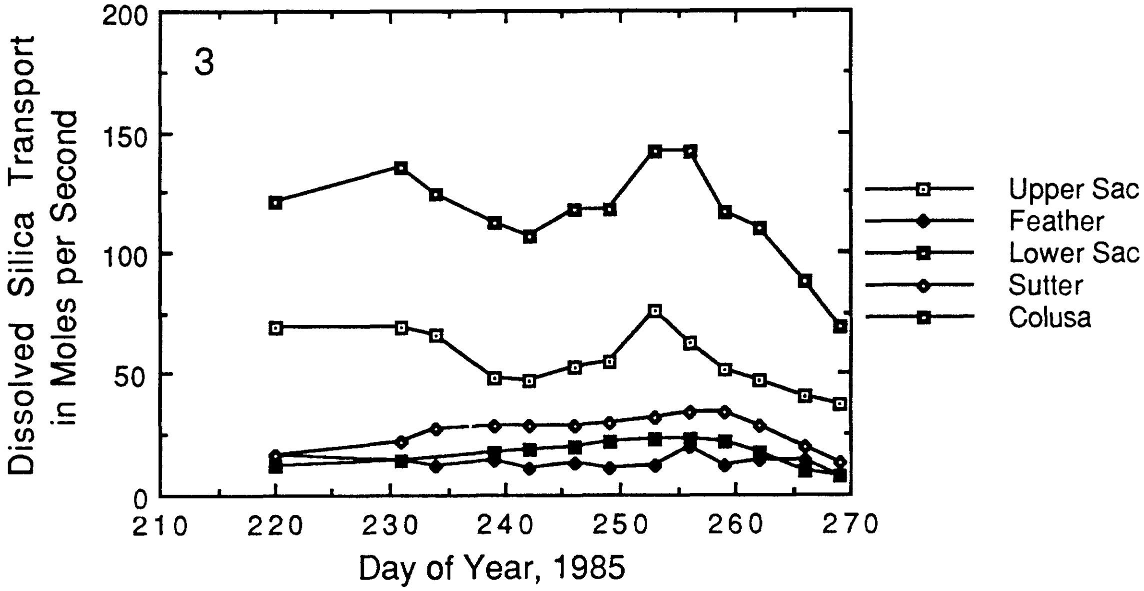
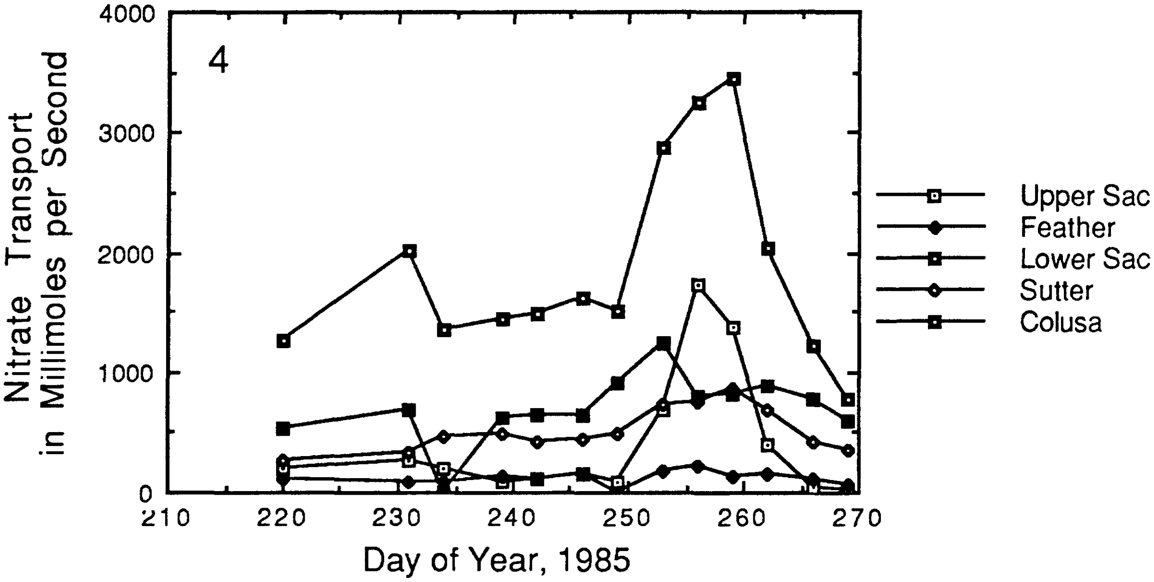


Figure B.-- continued.



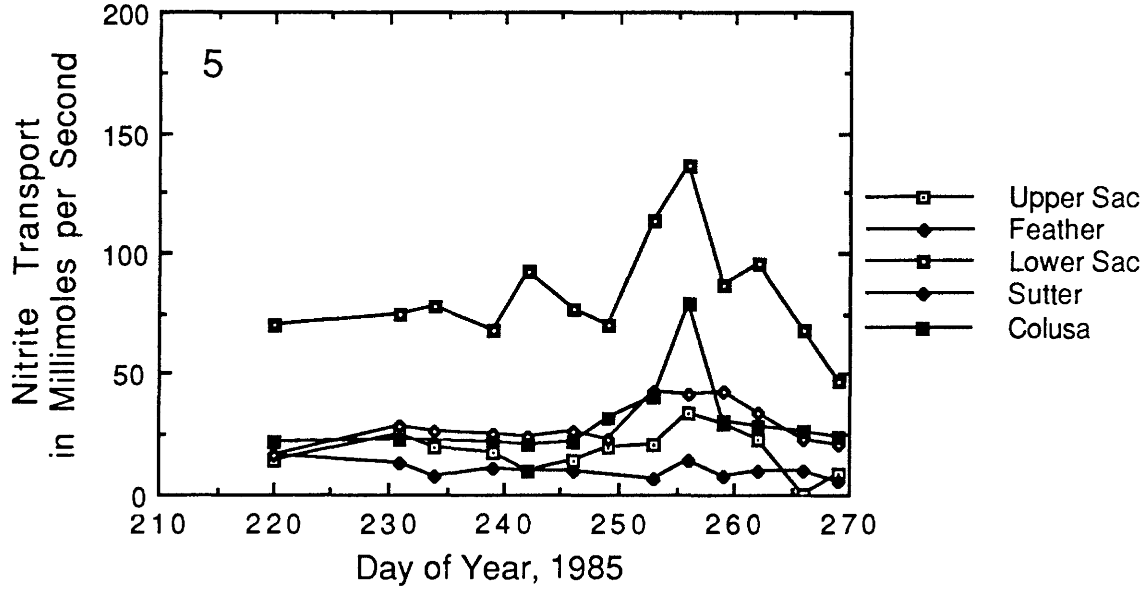
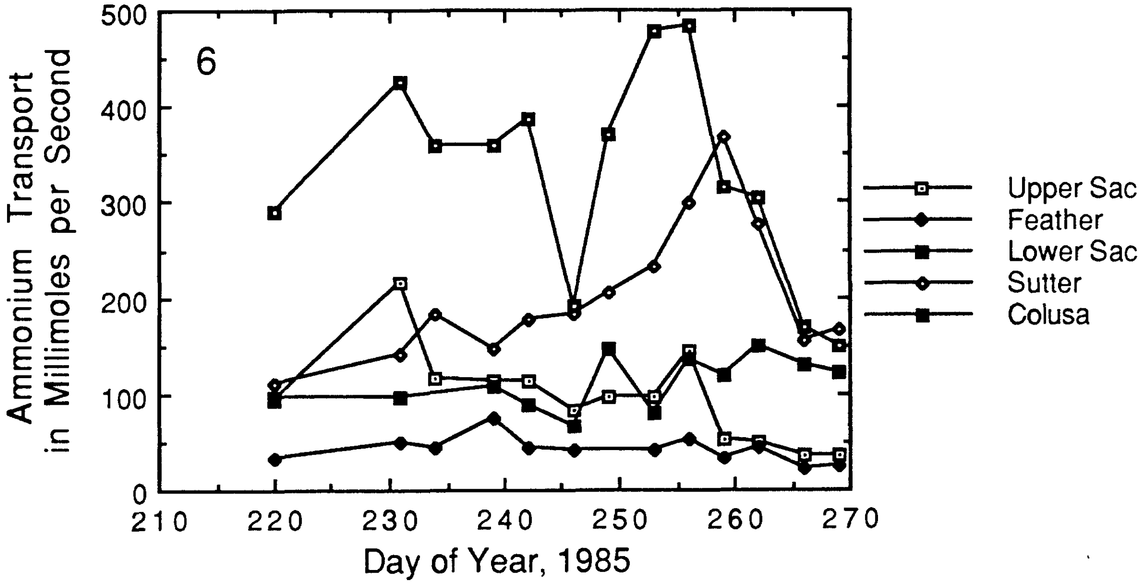


Figure B.-- continued.



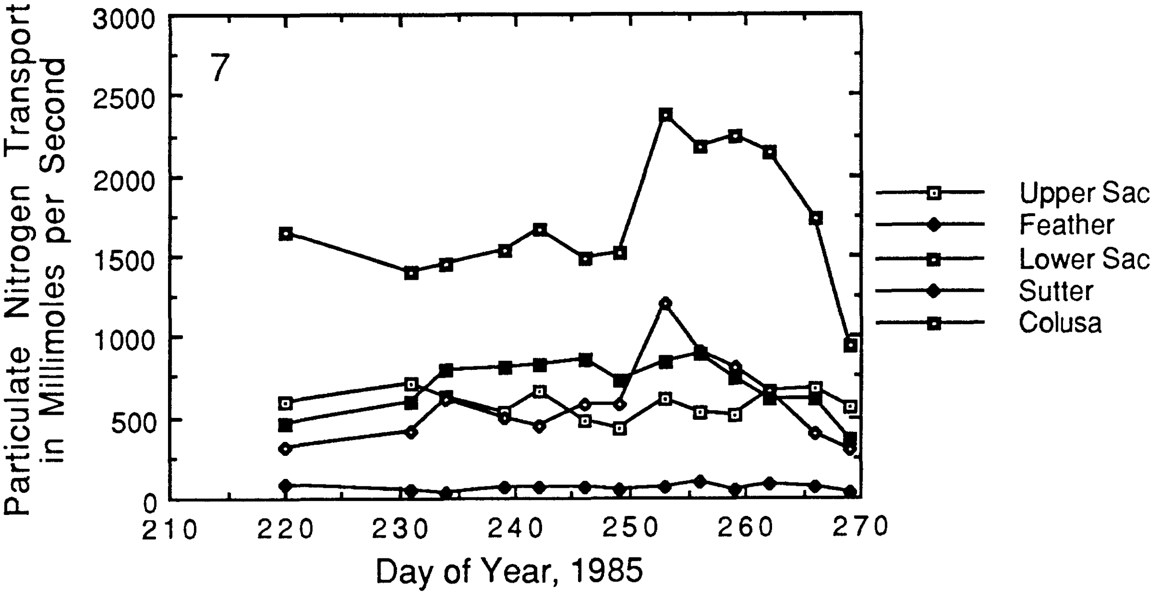
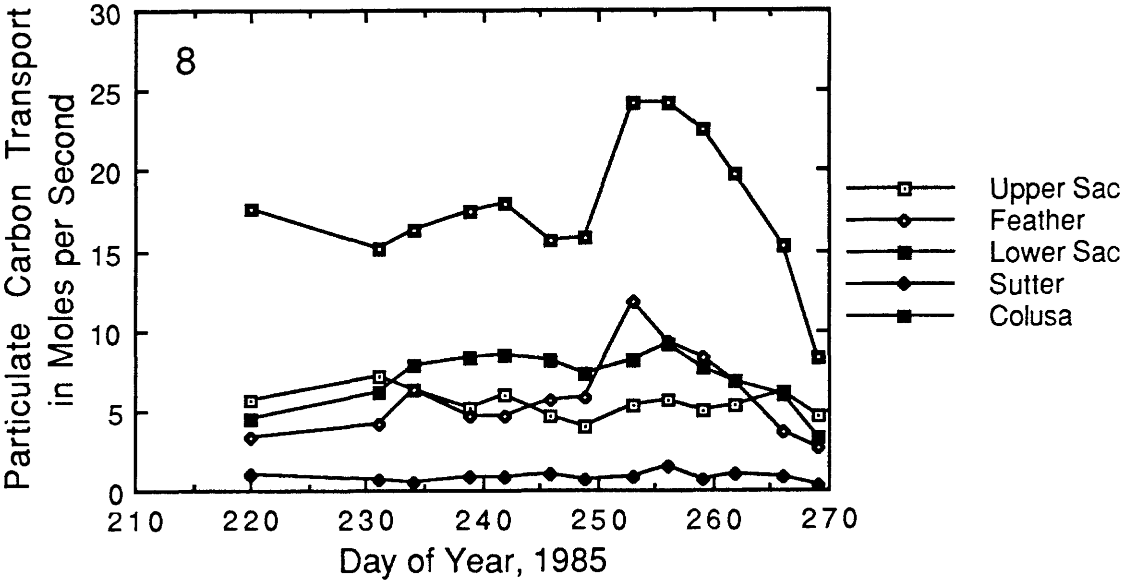


Figure B.-- continued.



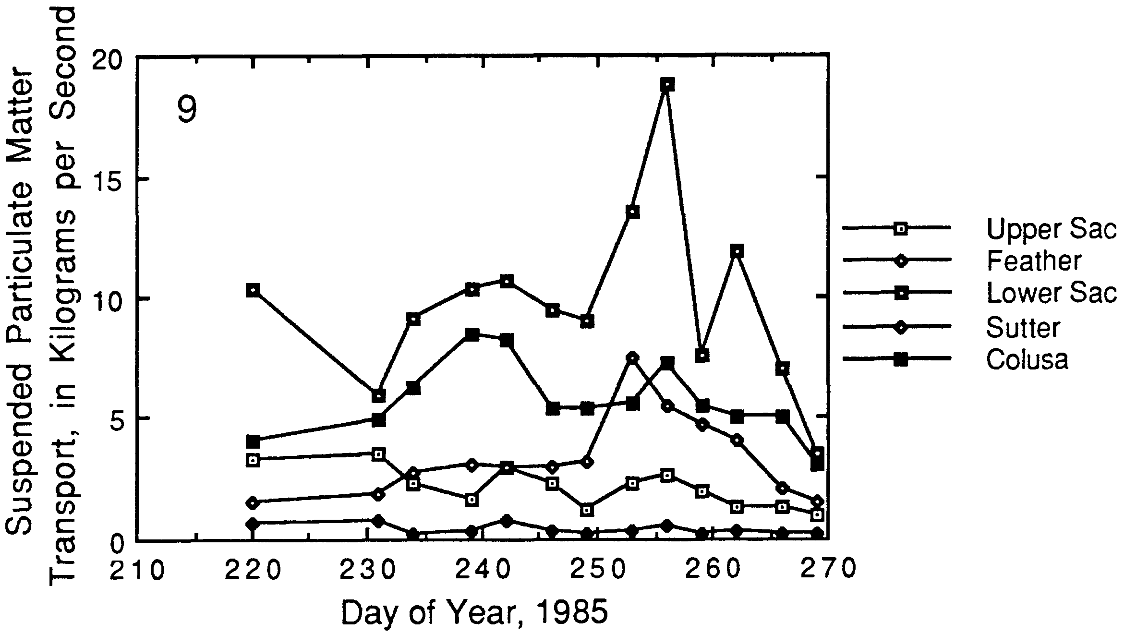


Figure B.-- continued.

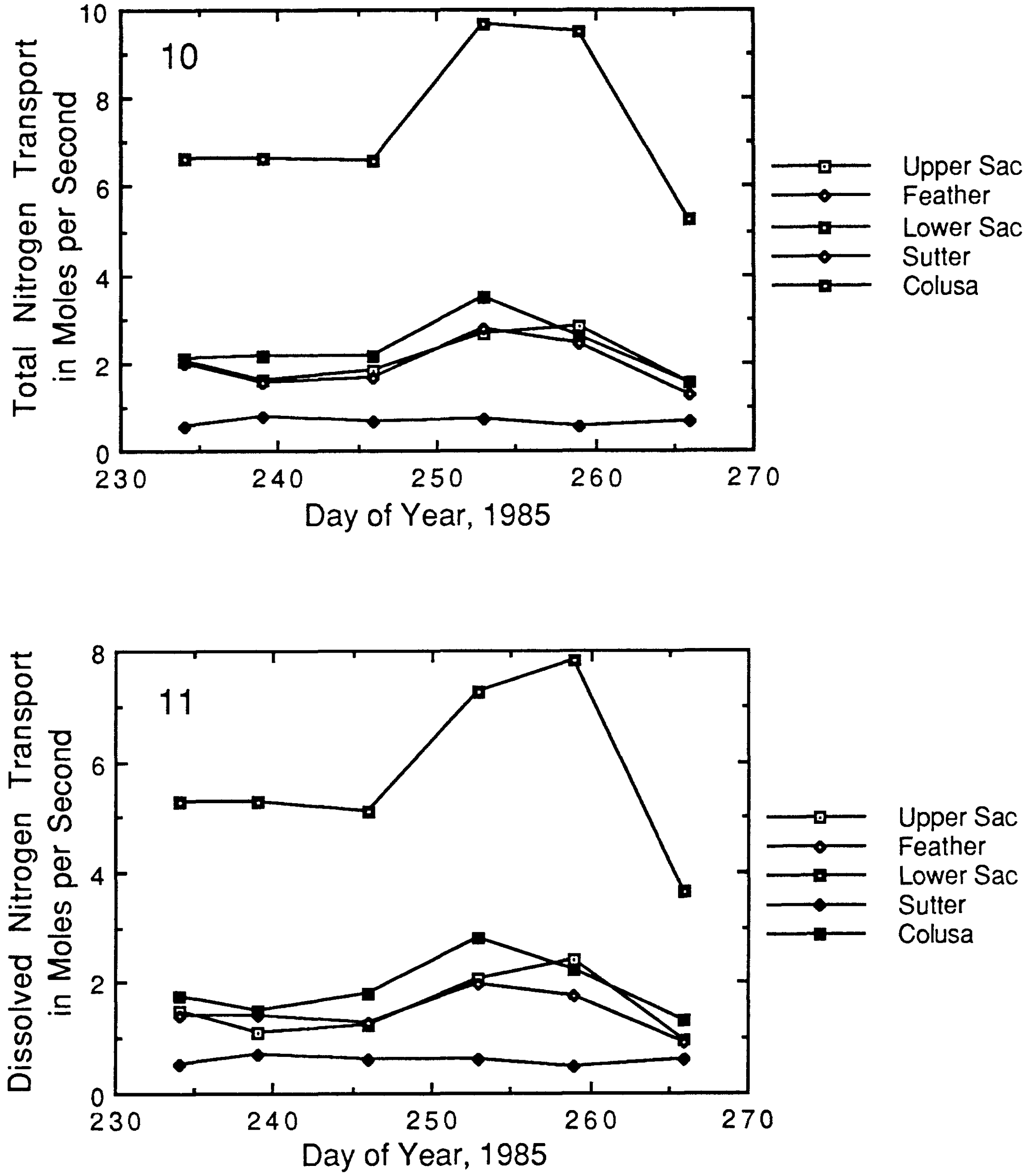
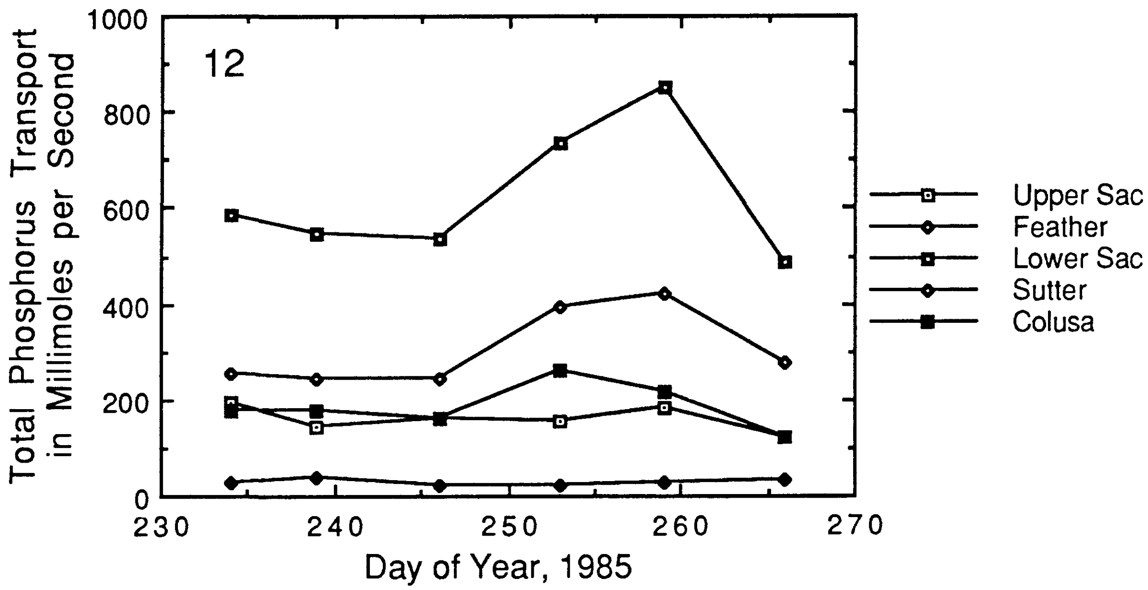


Figure B.-- continued.



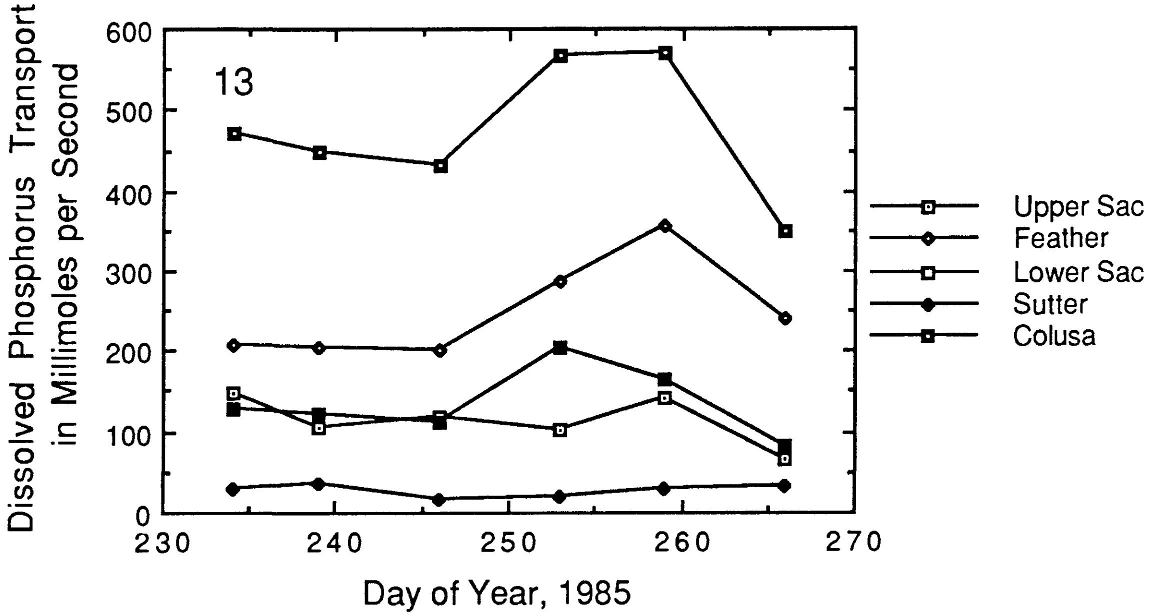


Figure B.-- continued.