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Water-Quality Assessment of the Sacramento River Basin, California—Water Quality of Fixed Sites, 1996–1998

Water-Resources Investigations Report 00-4247

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Water-Quality Assessment of the Sacramento River Basin, California—Water Quality of Fixed Sites, 1996–1998

by Joseph L. Domagalski *and* Peter D. Dileanis

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 00-4247

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

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Sacramento, California
2000

U.S. DEPARTMENT OF THE INTERIOR
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FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for specific contamination problems; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional- and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the U.S. Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 59 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 59 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch

Robert M. Hirsch
Chief Hydrologist

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CONVERSION FACTORS, ACRONYMS, AND ABBREVIATIONS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic meter (m^3)	0.0008107	acre-foot
cubic meter per second (m^3/s)	35.31	cubic foot per second
gram per day (g/d)	0.03527	ounce per day
kilogram (kg)	2.205	pound avoirdupois
kilogram per day (kg/d)	2.205	pound per day
kilogram per year (kg/yr)	2.205	pound per year
kilometer (km)	0.6214	mile
liter (L)	1.057	quart
square kilometer (km^2)	0.3861	square mile
meter (m)	1.094	yard
meter per second (m/s)	3.281	foot per second
milligram per liter (mg/L)	8.345	pound per million gallon

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

$$°F = (1.8 \times °C) + 32$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L).

Acronyms and Abbreviations

NAWQA, National Water-Quality Assessment (Program)
USGS, U.S. Geological Survey

ng/L, nanogram per liter
µg/L, microgram per liter
µm, micrometer
µS/cm, microsiemens per centimeter

Water-Quality Assessment of the Sacramento River Basin, California—Water Quality of Fixed Sites, 1996–1998

by Joseph L. Domagalski *and* Peter D. Dileanis

ABSTRACT

Water-quality samples were collected from 12 sites in the Sacramento River Basin, California, from February 1996 through April 1998. Field measurements (dissolved oxygen, pH, specific conductance, alkalinity, and water temperature) were completed on all samples, and laboratory analyses were done for suspended sediments, nutrients, dissolved and particulate organic carbon, major ions, trace elements, and mercury species. Samples were collected at four types of locations on the Sacramento River—large tributaries to the Sacramento River, agricultural drainage canals, an urban stream, and a flood control channel. The samples were collected across a range of flow conditions representative of those sites during the timeframe of the study. The water samples from the Sacramento River indicate that specific conductance increases slightly downstream but that the water quality is indicative of dilute water. Water temperature of the Sacramento River increases below Shasta Lake during the spring and summer irrigation season owing to diversion of water out of the river and subsequent lower flow. All 12 sites had generally low concentrations of nutrients, but chlorophyll concentrations were not measured; therefore, the actual consequences of nutrient loading could not be adequately assessed. Concentrations of dissolved organic carbon in samples from the Sacramento River and the major tributaries were generally low; the formation of trihalomethanes probably does not currently pose a problem when water from the Sacramento River and its major tributaries is chlorinated for drinking-water purposes. However, dissolved organic carbon concentrations were higher in the urban stream and in agricultural drainage canals, but were diluted upon mixing with the Sacramento River. The only trace element that currently poses a water-quality problem in the Sacramento River is mercury. A federal criterion for the protection of aquatic life was exceeded during this study, and floodwater concentrations of mercury were mostly higher than the criterion. Exceedances of water-quality standards happened most frequently during winter when suspended-sediment concentrations also were elevated. Most mercury is found in association with suspended sediment. The greatest loading or transport of mercury out of the Sacramento River Basin to the San Francisco Bay occurs in the winter and principally follows storm events.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) began full-scale implementation of the National Water-Quality Assessment (NAWQA) Program. The objectives of the NAWQA Program are to describe the status of and trends in the quality of a large, representative part of the nation's surface- and ground-water resources and to provide a sound scientific understanding of the primary natural and human factors affecting the quality of these resources (Leahy and others, 1990). Water-quality investigations began in a set of 20 study units in 1991. Investigations in a second set of study units, including the Sacramento River Basin, began in 1994 (Domagalski and Brown, 1994).

Fixed sites are an integral element of the surface-water design of the NAWQA study units (Gilliom and others, 1995). Fixed sites are located on streams where continuous streamflow is measured and samples are collected monthly to assess the broad-scale spatial and temporal character and the transport of inorganic constituents in stream water in relation to environmental setting and hydrologic conditions. Additional samples may be collected, especially following rainfall, so that the sampling represents a broad range of flow conditions. Twelve sites, which were sampled from February 1996 through April 1998, were selected in the Sacramento River Basin for the NAWQA Program.

Purpose and Scope

This report summarizes water-quality data collected at the fixed sites in the Sacramento River Basin NAWQA study unit from February 1996 through April 1998, evaluates the effects of land use on water quality at the fixed sites, and presents loads for mercury and methylmercury transported in the Sacramento River. The report focuses on those water-quality constituents collected during regular monthly sampling and high-flow sampling. The data collected consist of constituents measured in the field, major inorganic cations and anions, trace elements, mercury, dissolved and suspended organic carbon, nutrients, and suspended sediment. The variability of water quality between and within land uses was examined to evaluate the effect of land uses. Load calculations were completed for mercury and methylmercury because of their potential to adversely affect the beneficial uses of water at downstream locations.

Description of the Sacramento River Basin Study Unit

The Sacramento River Basin (fig. 1) covers nearly 70,000 km^2 in the north-central part of California. The Sacramento River is the largest river in California, with an average annual runoff of 27,126,000,000 m^3 (California Department of Water Resources, 1993). The basin includes all or parts of six physiographic provinces—the Great Basin, the Middle Cascade Mountains, the Sierra Nevada, the Klamath Mountains, the Sacramento Valley, and the Coast Ranges (fig. 2). The Sacramento Valley physiographic province is the low-lying part of the basin; all other physiographic provinces are mountainous. Land cover of the mountainous parts of the study unit is principally forest, except in parts of the Coast Ranges and the Great Basin where land cover is forest land and rangeland. More detailed information on the physiographic provinces of the Sacramento River Basin is given in a report by Domagalski and others (1998).

The Sacramento Valley is the northern part of the Central Valley of California and is fully located in the study unit. The Sacramento Valley has the largest population in the study unit and, consequently, the greatest effects or potential effects on surface and ground water are likely to occur there. The Sacramento Valley also has the greatest water use in the basin; therefore, most of the fixed sites were selected from that physiographic province. Although most adverse effects on water quality in the Sacramento River are likely to occur within the Sacramento Valley physiographic province, adverse effects on water quality also occur in the other physiographic provinces. Previous mining activities in the Klamath Mountains have resulted in acid mine drainage into Keswick Reservoir, along with the associated metals cadmium, copper, and zinc. Mercury, from previous mining activities in the Coast Ranges, enters the Sacramento Valley through Cache Creek and Putah Creek. Although neither creek flows directly into the Sacramento River during low-flow conditions, mercury can be transported to downstream receiving waters, including the San Francisco Bay, during stormwater runoff conditions. Mercury from historical gold mining operations has affected fish populations in streams and reservoirs immediately downstream of the mines (May and others, 2000).

The Sacramento Valley supports a diverse agricultural economy, much of which depends on the availability of irrigation water. More than 8,090 km^2 is irrigated. The major crops are rice, fruits and nuts, tomatoes, sugar beets, corn, alfalfa, and wheat. Dairy products also are an important agricultural commodity. The soils of the Sacramento Valley primarily are clay with slow to very slow infiltration rates (Soil Conservation Service, 1993). The largest cities of the basin are in the Sacramento Valley and include Chico,

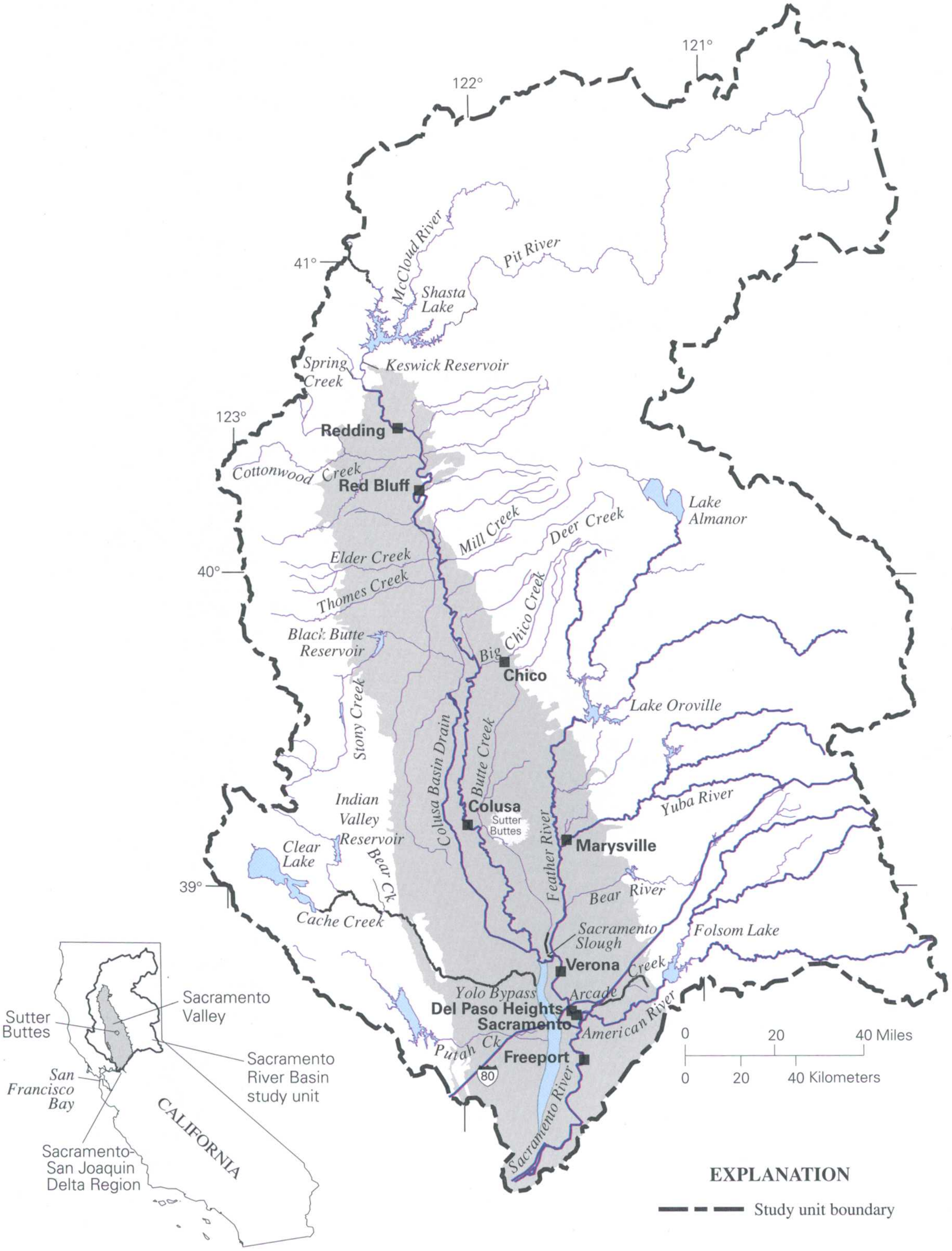


Figure 1. The Sacramento River Basin, California.

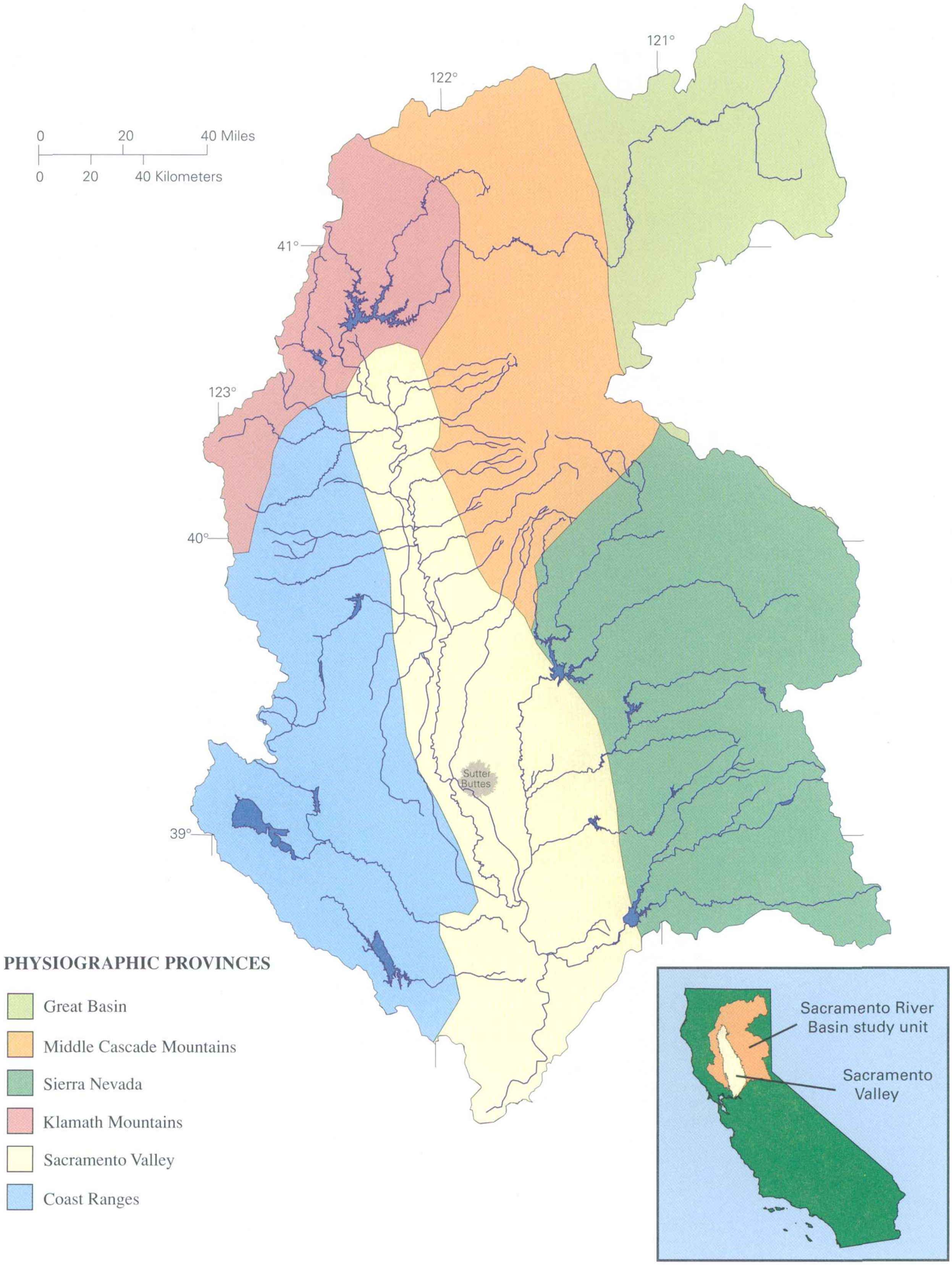


Figure 2. Physiographic provinces of the Sacramento River Basin, California.

Red Bluff, Redding, and Sacramento. The population of the Sacramento metropolitan area is more than 1 million, which is nearly one-half of the population of the study unit (U.S. Department of Commerce, 1992).

The average annual precipitation in the Sacramento River Basin is 91.4 cm, most of which falls during November through March. Because little or no rain falls during the summer growing season, irrigation water is needed for agriculture. Two major hydrological events occurred during this study. The first was a large flood, which started about January 1, 1997, that affected most of the Sacramento River below Shasta Lake and tributaries to the Sacramento River, especially the Feather and Yuba rivers. The second was the El Niño southern oscillation, which occurred during the winter of 1997–1998. During El Niño winters, wind conditions over the Pacific Ocean cause warmer than normal water to build along the Pacific Coast. An El Niño winter typically results in higher than normal precipitation in northern California, as in 1997–1998, because of changes in the location of the jet stream.

All the major rivers of the basin—the Sacramento, the Feather, the American, and the Yuba—are impounded outside the boundary of the Sacramento Valley (fig. 1). The upper Sacramento River, the McCloud River, and the Pit River supply water to Shasta Lake, which has a capacity of over 5.6 billion cubic meters. Lake Oroville, on the Feather River, has a capacity of over 4.3 billion cubic meters. The reservoirs are managed to provide flood protection in the winter, water for irrigation to farms in the spring and summer, and water supply for cities throughout the year. Snowmelt, which is the water entering most of the reservoirs, generally is of high quality. However, water entering reservoirs of the Sierra Nevada is degraded by mercury from past gold mining.

The rocks of the Sacramento River Basin are of a diverse assemblage. The Coast Ranges consist of ocean sediments and volcanic rocks. The Klamath Mountains include accreted terrains, oceanic crust, and subduction zone complexes. The Cascade Mountains and Great Basin consist predominantly of volcanic rocks. The Sierra Nevada assemblage includes granitic plutons and volcanic, sedimentary, and metamorphic rocks. The Sacramento Valley is composed mainly of a thick assemblage of sediments derived from these adjacent highlands.

WATER-QUALITY ISSUES

A liaison committee of federal, state, and local water-management and water-quality agencies and citizen groups was formed in 1994 to discuss the major water-quality issues affecting the Sacramento River Basin and to assist in site selection and determining sampling frequency. Also in 1994, a watershed group, the Sacramento River Watershed Program, was formed for the express purpose of managing water quality in the Sacramento River through a stakeholder process. The Sacramento River Watershed Program comprises all or most of the previously mentioned liaison committee. In 1994, the major water-quality issues affecting the basin were (1) trace metals, including mercury, copper, lead, and cadmium; (2) pesticides from rice farming (molinate, thiobencarb, and carbofuran); (3) pesticides used on orchards (diazinon, chlorpyrifos, methidathion, and other organophosphate insecticides); and (4) urban runoff of pesticides, especially diazinon and chlorpyrifos. Although a major problem in the San Joaquin River Basin to the south, selenium concentrations have not affected the water quality of streams or rivers of the Sacramento River Basin. In 1999, the Sacramento River Watershed Program considered mercury, organophosphate insecticides, and unidentified toxicity to be the most critical water-contaminant problems affecting this basin (Cooke and Connor, 1998).

Further insight into water-quality problems affecting the streams of the Sacramento River Basin can be obtained from the most recent (1998) 303(d) listing of impaired water bodies provided by the State Water Resources Control Board of California (U.S. Environmental Protection Agency, accessed October 1, 1999). The Clean Water Act requires that all states maintain the listing. A listing for impaired water bodies of the Sacramento River Basin is given in table 1.

The principal water-quality impairments, as noted in the 303(d) list, are trace metals, including mercury, and organophosphate pesticides such as diazinon and chlorpyrifos. Only the Pit River and Clear Lake are listed as water-quality impaired because of nutrients. Trace metals resulting from previous mining activities in the basin are a source of water-quality problems. The locations of historical mercury and gold mines are shown on figure 3, and the locations of historical copper, lead, and zinc mines are shown on figure 4. Gold mining included the use of

Table 1. Impaired water bodies of the Sacramento River Basin, California

[PCBs, polychlorinated biphenyls. Modified from 303(d) list (U.S. Environmental Protection Agency, accessed October 1, 1999]

Water body	Impairment	Source of impairment	Priority
Arcade Creek	Chlorpyrifos	Urban runoff	Medium
	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff	Medium
Cache Creek	Unknown toxicity	Unknown	Medium
	Mercury	Mining	High
Chicken Ranch Slough	Chlorpyrifos	Urban runoff/storm sewers	Medium
	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff/storm sewers	Medium
Clear Lake	Mercury	Mining	High
	Nutrients	Unknown	Low
Colusa Basin Drain	Unknown toxicity	Agriculture	Medium
	Carbofuran	Agriculture	Medium
	Organochlorine pesticides	Agriculture	Medium
	Malathion	Agriculture	Medium
	Methyl parathion	Agriculture	Medium
Davis Creek Reservoir	Mercury	Mining	Medium
Dolly Creek	Copper	Mining	Medium
	Zinc	Mining	Medium
Elder Creek	Chlorpyrifos	Urban runoff/storm sewers	Medium
	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff/storm sewers	Medium
Elk Grove Creek	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff/storm sewers	Medium
Fall River	Sedimentation/siltation	Agriculture/grazing	Medium
	Sedimentation/siltation	Silviculture	Medium
	Sedimentation/siltation	Highway/road/bridge construction	Medium
French Ravine	Bacteria	Land disposal	Low
Harley Gulch	Mercury	Mining	Medium
Horse Creek	Cadmium	Mining	Low
	Copper	Mining	Low
	Lead	Mining	Low
	Zinc	Mining	Low

Table 1. Impaired water bodies of the Sacramento River Basin, California—*Continued*

Water body	Impairment	Source of impairment	Priority
Humbug Creek	Copper	Mining	Low
	Mercury	Mining	Low
	Zinc	Mining	Low
	Sedimentation/siltation	Mining	Low
James Creek	Mercury	Mining	Low
	Nickel	Mining	Low
Kanaka Creek	Arsenic	Mining	Low
Keswick Reservoir	Cadmium	Mining	Medium
	Copper	Mining	Medium
	Zinc	Mining	Medium
Lake Berryessa	Mercury	Mining	High
Little Backbone Creek	Cadmium	Mining	Medium
	Copper	Mining	Medium
	Zinc	Mining	Medium
	Acid mine drainage	Mining	Medium
Little Cow Creek	Cadmium	Mining	Low
	Copper	Mining	Low
	Zinc	Mining	Low
Little Grizzly Creek	Copper	Mine tailings	Medium
	Zinc	Mine tailings	Medium
Lower American River	Unknown toxicity	Unknown	Low
	Mercury	Mining	Medium
	Organochlorine pesticides	Urban runoff	Low
Lower Feather River	Unknown toxicity	Unknown	Medium
	Mercury	Mining	Medium
	Diazinon	Agriculture	High
	Diazinon	Urban runoff	High
	Organochlorine pesticides	Agriculture	Low
Morrison Creek	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff	Medium
Natomas East Main Drain	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff/storm sewers	Medium
	PCBs	Industrial point sources	Low
	PCBs	Urban runoff/storm sewers	Low

Table 1. Impaired water bodies of the Sacramento River Basin, California—*Continued*

Water body	Impairment	Source of impairment	Priority
Pit River	Nutrients	Agriculture	Low
	Nutrients	Agriculture/grazing	Low
	Organic enrichment/low dissolved oxygen	Agriculture	Low
	Organic enrichment/low dissolved oxygen	Agriculture/grazing	Low
	Temperature	Agriculture	Low
	Temperature	Agriculture/grazing	Low
Sacramento River (lower)	Unknown toxicity	Unknown	Medium
	Mercury	Mining	High
	Diazinon	Agriculture	High
Sacramento River (upper)	Cadmium	Mining	High
	Copper	Mining	High
	Zinc	Mining	High
Sacramento Slough	Mercury	Unknown	Medium
	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff	Medium
Shasta Lake	Cadmium	Mining	Low
	Copper	Mining	Low
	Zinc	Mining	Low
Spring Creek	Cadmium	Mining	High
	Copper	Mining	High
	Zinc	Mining	High
	Acid mine drainage	Mining	High
Strong Ranch Slough	Chlorpyrifos	Urban runoff/storm sewers	Medium
	Diazinon	Agriculture	Medium
	Diazinon	Urban runoff/storm sewers	Medium
Sulfur Creek	Mercury	Mining	High
Town Creek	Cadmium	Mining	Low
	Copper	Mining	Low
	Lead	Mining	Low
	Zinc	Mining	Low
West Squaw Creek	Cadmium	Mining	Medium
	Copper	Mining	Medium
	Lead	Mining	Medium
	Zinc	Mining	Medium
Willow Creek	Copper	Mining	Low
	Zinc	Mining	Low
	Acid mine drainage	Mining	Low

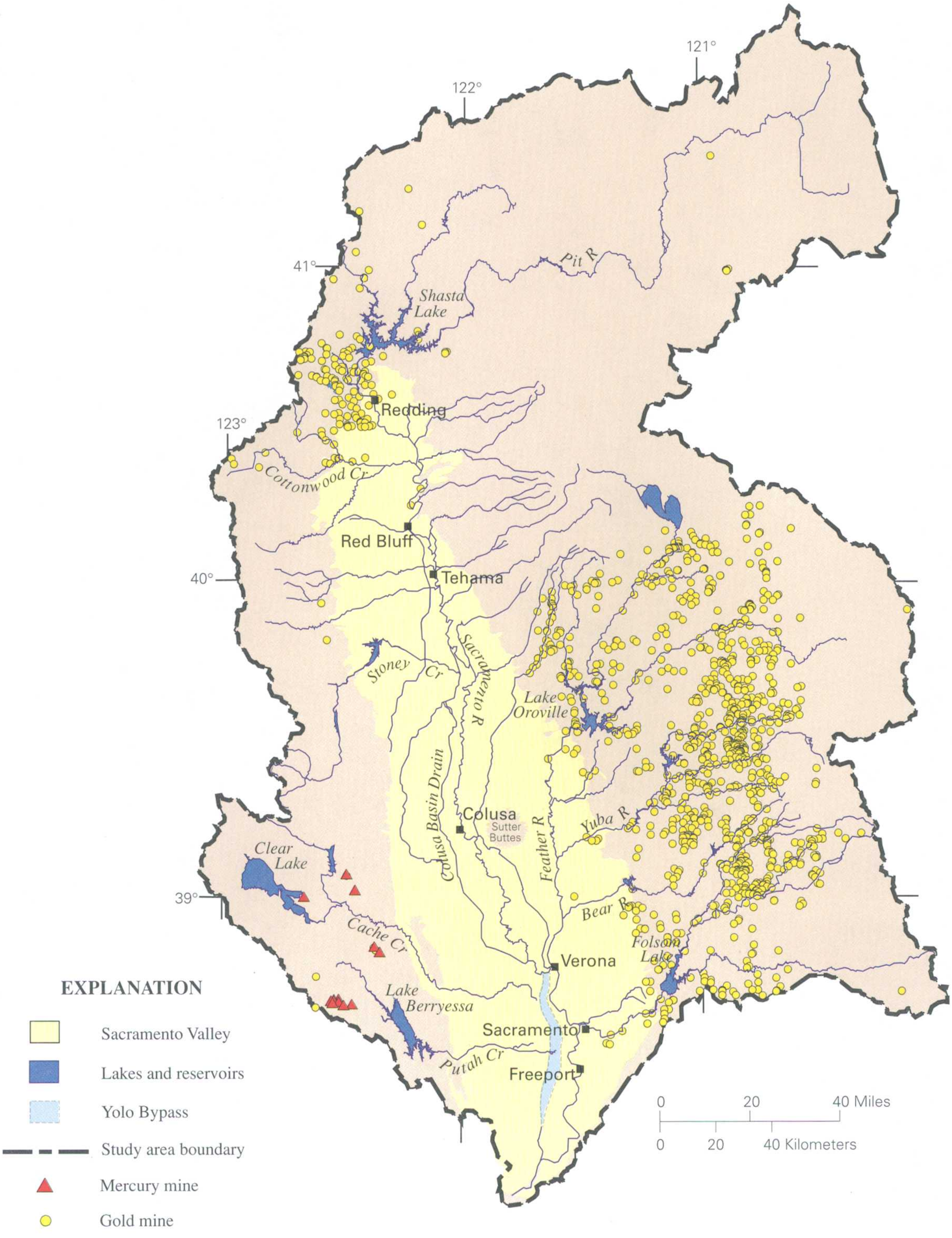


Figure 3. Locations of mercury and gold mines in the Sacramento River Basin, California.

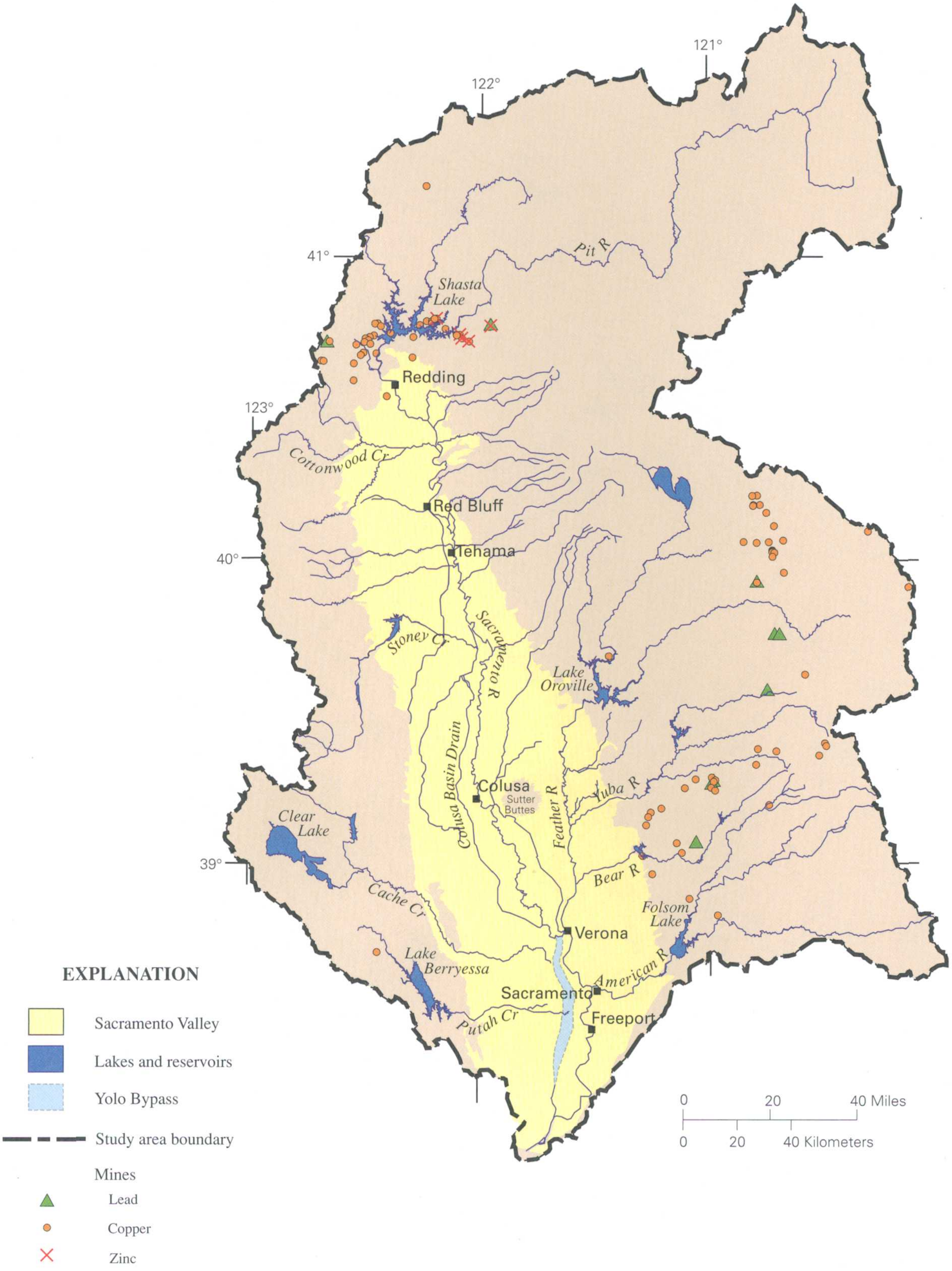


Figure 4. Locations of lead, copper, and zinc mines in the Sacramento River Basin, California.

mercury amalgamation to recover the gold from ore-bearing minerals.

SELECTION OF FIXED SITES

The NAWQA study design includes two types of fixed sites—integrator sites and indicator sites (Gilliom and others, 1995). Integrator sites are selected to document water-quality conditions of rivers in heterogeneous large basins that are affected by complex combinations of environmental settings. Indicator sites are selected to document water-quality conditions of rivers or streams in relatively homogeneous areas, which generally are in one physiographic province and are characterized by a continuous type of land use.

The study focused on the water quality of the lower Sacramento River (below Shasta Lake) and the major tributaries to that reach of the Sacramento River, where the most serious effects on water quality are likely or the consequences of degraded water quality are likely acutely felt. The Sacramento River above Shasta Lake generally has good water quality because the land use, or land cover, is primarily forest land. The same is true for the McCloud River. The other major river above Shasta Lake, the Pit River, is susceptible to degraded water quality because of agricultural and urban land use. A series of dams, built for hydroelectric power generation, are present along a major reach of the Pit River. These impoundments have created a series of small reservoirs, making the interpretation of water quality data or the interpretation of potential water quality impacts on aquatic biological communities problematic. For these reasons, the Pit River was not selected for sampling. Because of the large size of the Sacramento River and associated tributaries, most (8 of 12) of the fixed sites are classified as integrator sites. Four of the integrator sites are on the Sacramento River (fig. 5)—the Sacramento River above Bend Bridge near Red Bluff, the Sacramento River at Colusa, the Sacramento River at Verona, and the Sacramento River at Freeport (the most downstream location). During high-flow conditions, such as when the flow of the Sacramento River at Colusa exceeds 850 m^3/s, water is diverted to a channel east of the river to prevent flooding in downstream regions, including the city of Sacramento. When the flow of the Sacramento River at Verona exceeds approximately 1,560 m^3/s, water is diverted to another flood control channel, the Yolo Bypass (fig. 1). The Yolo Bypass at Interstate 80 near West Sacramento is a fixed site during those high-flow conditions (fig. 5). It is necessary to sample both the Sacramento River at Freeport and the Yolo Bypass at Interstate 80 near West Sacramento to determine mass loadings and water-quality effects on downstream receiving water bodies during those high flows. Other integrator sites are on major tributaries to the Sacramento River—the Yuba River at Marysville, the Feather River near Nicolaus, and the American River at Sacramento (fig. 5).

Four indicator sites were selected for the Sacramento River Basin NAWQA study—the Cache Creek at Rumsey (mining land use), the Colusa Basin Drain at Road 99E near Knights Landing (agricultural land use), the Sacramento Slough near Knights Landing (agricultural land use), and the Arcade Creek near Del Paso Heights (urban land use) (fig. 5).

Site name and number, drainage area, and mean streamflow for the period of study of the fixed sites are given in table 2. Historical streamflow information (table 3) indicates that 1983 was a year of high streamflow in the basin, and 1977 was a year of drought. Highest peak instantaneous flows were recorded at three sites during the period of this investigation. Streamflow data for all but three sites were obtained from USGS gaging stations. Streamflow data for the Sacramento Slough near Knights Landing and the Colusa Basin Drain at Road 99E near Knights Landing were obtained from the California Department of Water Resources Northern District (California Department of Water Resources, written commun., 1999). Streamflow data for the Cache Creek at Rumsey site were obtained from the California Department of Water Resources Central District (California Department of Water Resources, written commun., 1999).

Sacramento River Above Bend Bridge Near Red Bluff

The Sacramento River above Bend Bridge near Red Bluff site (fig. 5, site 1) is located 83.7 km downstream from the dam on Shasta Lake. This site was chosen because it is in the upper part of the basin and below Shasta Lake. Streamflow is greatly influenced by the managed releases from Shasta Lake and, during the rainy season, by stormwater runoff. There are no artificial levees at this location, and therefore, the stream channel is in a natural state at this location. The area of the drainage basin at this site is 23,569 km^2

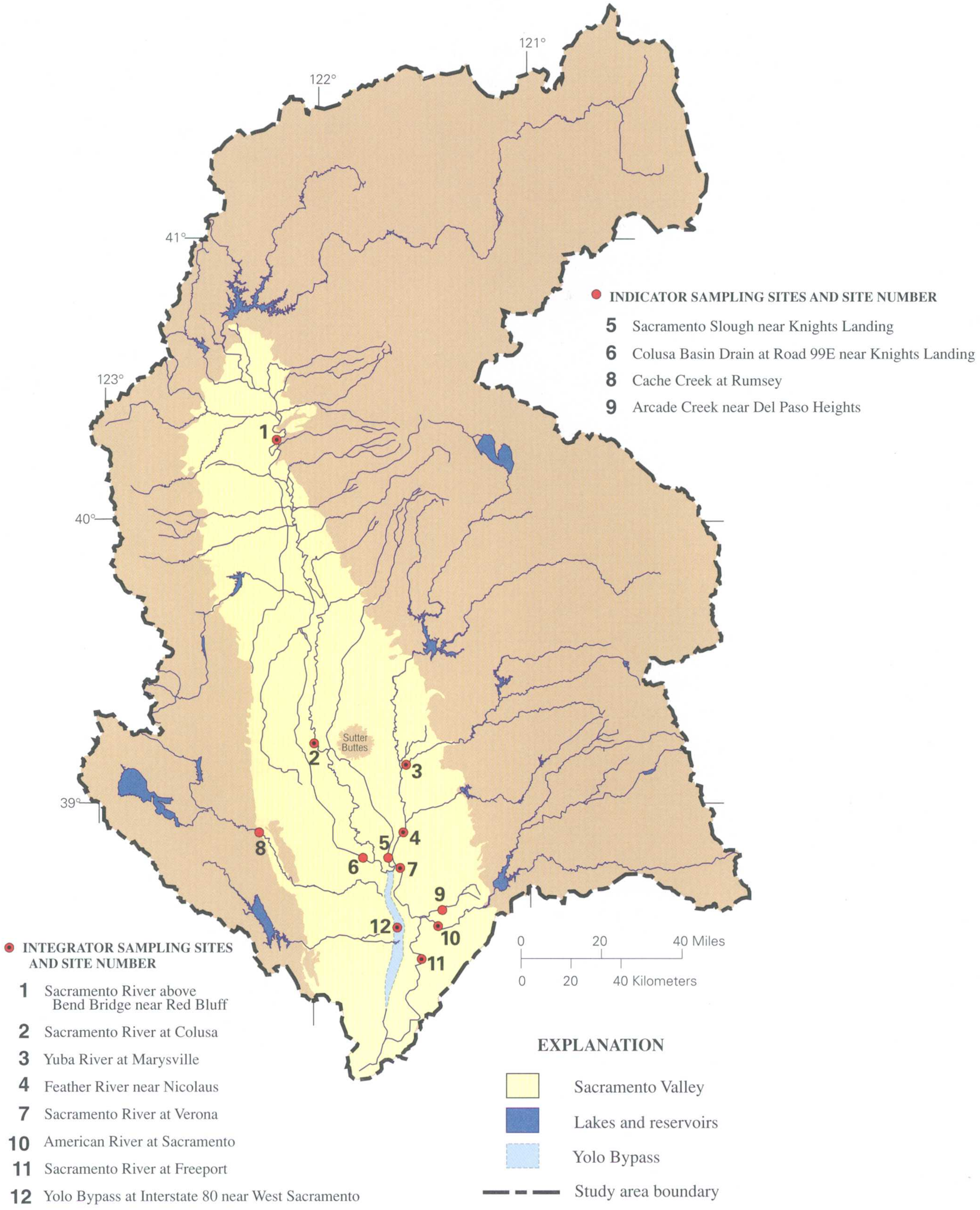


Figure 5. Locations of sampling sites and site numbers in the Sacramento River Basin, California.

Table 2. Site name, U.S. Geological survey identification number, drainage area, type of site, and mean streamflow for the period of this study, Sacramento River Basin, California, 1996–1998

[USGS, U.S. Geological Survey. na, not available; km^2, square kilometer; m^3/s, cubic meter per second]

Site number	Site name	USGS identification no.	Drainage area (km^2)	Fixed-site type	Mean streamflow (m^3/s) (period of study)
1	Sacramento River above Bend Bridge near Red Bluff	11377100	23,621	Integrator	524.1
2	Sacramento River at Colusa	11389500	31,728	Integrator	457.2
3	Yuba River at Marysville	11421500	3,730	Integrator	124.2
4	Feather River near Nicolaus	11425000	5,776	Integrator	378.3
5	Sacramento Slough near Knights Landing	11391100	3,370	Indicator	60.6
6	Colusa Basin Drain at Road 99E near Knights Landing	11390890	4,274	Indicator	7.6
7	Sacramento River at Verona	11425500	45,817	Integrator	813.4
8	Cache Creek at Rumsey	11451800	2,950	Indicator	52.9
9	Arcade Creek near Del Paso Heights	11447360	87	Indicator	1.0
10	American River at Sacramento	11447000	5,180	Integrator	171.3
11	Sacramento River at Freeport	11447650	59,570	Integrator	983.3
12	Yolo Bypass at Interstate 80 near West Sacramento	11453120	59,389	Integrator	na

Table 3. Annual mean discharge, highest annual mean discharge, lowest annual mean discharge, and instantaneous peak flow for historical streamflow at basic fixed sites, Sacramento River Basin, California, 1996–1998

[Mean discharge and peak flow are in cubic meters per second. Period of record keeping or dates of peak flow shown in parentheses. na, not available]

Site number	Site name	Mean discharge: Annual	Mean discharge: Highest annual	Mean discharge: Lowest annual	Instantaneous peak flow
1	Sacramento River above Bend Bridge near Red Bluff	372 (1964–98)	721 (1983)	184 (1991)	4,814 (12/22/1964)
2	Sacramento River at Colusa	330 (1946–98)	617 (1983)	161 (1977)	1,467 (3/04/1983)
3	Yuba River at Marysville[1]	71 (1970–98)	164 (1982)	6.5 (1977)	4,304 (1/02/1997)
4	Feather River near Nicolaus	240 (1943–83)	572 (1983)	48 (1977)	10,110 (12/23/1955)
5	Sacramento Slough near Knights Landing	na	na	na	na
6	Colusa Basin Drain at Road 99E near Knights Landing	na	na	na	na
7	Sacramento River at Verona	565 (1946–98)	1,109 (1983)	203 (1977)	2,662 (1/02/1997)
8	Cache Creek at Rumsey	na	na	na	na
9	Arcade Creek near Del Paso Heights	0.5 (1963–98)	1 (1998)	0.075 (1977)	94 (2/03/1998)
10	American River at Sacramento	108 (1956–98)	251 (1983)	22 (1977)	3,795 (2/19/1986)
11	Sacramento River at Freeport	676 (1949–98)	1,328 (1983)	215 (1977)	3,313 (2/19/1986)
12	Yolo Bypass at Interstate 80 near West Sacramento	na	na	na	7,505 (12/25/1964)

[1] Data from nearby station, Yuba River near Marysville.

and includes parts or all of the Great Basin, Middle Cascade Mountains, Klamath Mountains, Coast Ranges, and Sacramento Valley physiographic provinces (figs. 2 and 6). Land cover in the area above this site is mainly forest land (about 72 percent). Cropland and pasture is 4.3 percent of the land use, and range-land covers 20 percent. The areal distribution and percentage of all land uses are shown on figure 6.

The land-use/land-cover classifications are from remote sensing data (Fegeas and others, 1983), and the system of land-use classification used throughout this report is described by Anderson and others (1976). Although the remote sensing land-use or land-cover data described in this report are from the 1970s, the data have not changed significantly except for the extent of the urbanized regions, especially around Sacramento. Mining activities take place or have taken

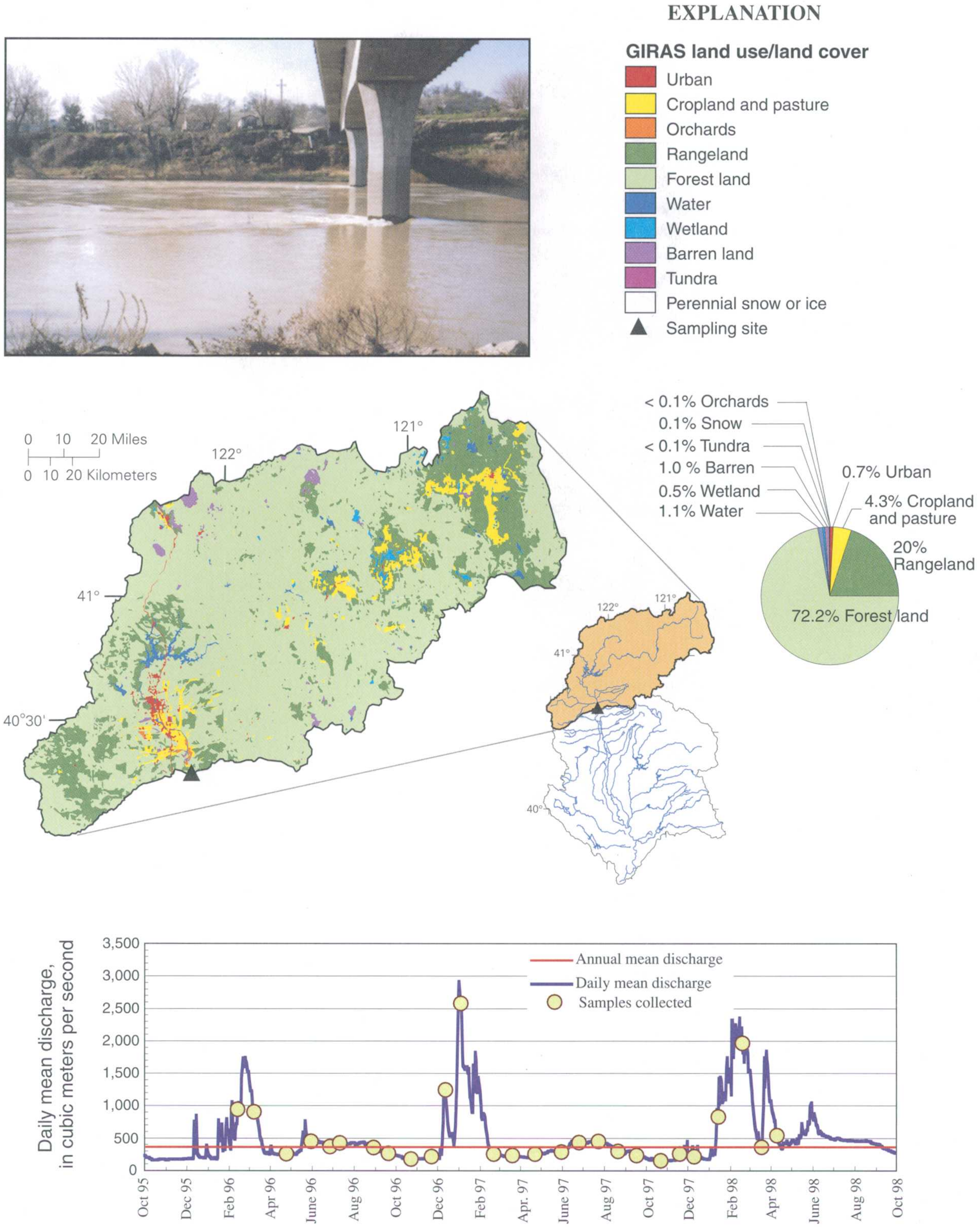


Figure 6. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Sacramento River above Bend Bridge near Red Bluff sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

place in the Klamath Mountains. However, the individual mines are too small to be detected by remote sensing and, therefore, are not included in the percenttage classification or on this (fig. 6) or other land-use maps in this report. However, as shown on figures 3 and 4, mining was an important land use within the Klamath Mountains, just west of Shasta Lake. One large mining operation, the Iron Mountain mine site, is located in this region. Iron, as well as copper and zinc, was recovered from ore-bearing minerals. Other trace elements in the ore include cadmium and lead.

Land-use effects from mining activities are likely to be detected at this location. A hydrograph of daily mean discharge for the period of this study is shown on figure 6. A total of 27 samples were collected for water-quality analysis for a range of flow conditions.

Sacramento River at Colusa

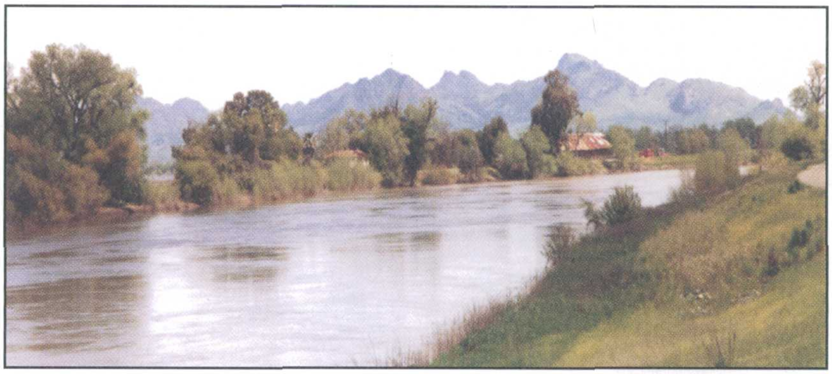
The Sacramento River at Colusa site (fig. 5, site 2) is located 161 km downstream from the Sacramento River above Bend Bridge near Red Bluff site. The stream channel has been modified at and below this location by artificial levees for flood control. Owing to the levees, most runoff from adjacent farmland does not reach the river. In addition, a weir has been constructed (east of the main channel) to divert water from the main channel into a flood control channel when flow in the Sacramento River exceeds about 850 m^3/s. Land-use classification (Anderson and others, 1976) at this site is shown on figure 7. Forest land is the predominant land use or land cover (about 68 percent). Rangeland is about 22 percent of the total, and cropland and pasture plus orchards is only about 7 percent of the total. A hydrograph of daily mean discharge at this site for the period of this study also is shown on figure 7. A total of 28 samples were collected for water-quality analysis for a range of flow conditions at this site.

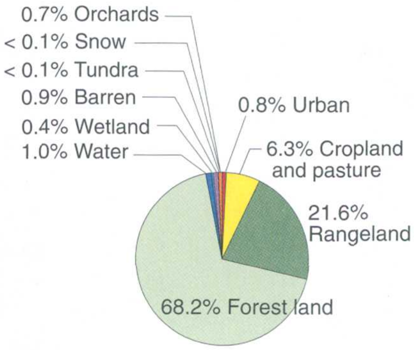
Yuba River at Marysville

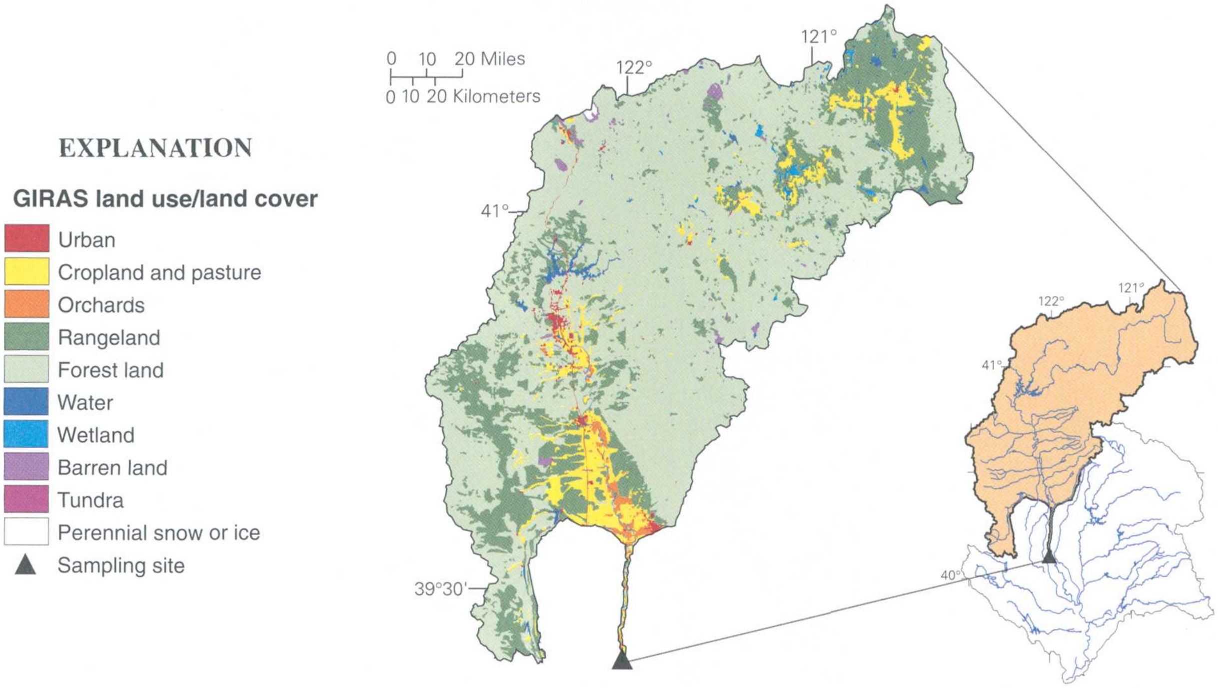
The Yuba River is the largest tributary to the Feather River, and the site at Marysville (fig. 5, site 3) was selected because of its proximity (3 km) to the confluence. Because levees were constructed on the lower Yuba River for flood control, only some of the runoff from adjacent lands can reach the river. Forest land is the primary land use and land cover (Anderson and others, 1976) for this basin (fig. 8). Forest land makes up about 85 percent of the land cover. The forest land in the Yuba River Basin is located in the foothills of the Sierra Nevada, which also contains a substantial amount of gold mining, including placer and hard-rock mines. Individual mines are too small to appear on remote sensing images and are not part of the Anderson and others (1976) classification. The location of gold mines is shown on figure 3. Mercury was used in the basin to recover gold from both placer deposits and ore-bearing minerals. Residual mercury from those operations has been detected in invertebrate and fish communities nearby and downstream from the gold mining operations (Slotton and others, 1997; May and others, 2000). According to Slotton and others (1997), reservoirs constructed just downstream from the gold mining operations act as a sink for mercury. However, mercury transported to the lower Yuba drainage prior to reservoir construction probably is still in the streambed sediment. A hydrograph for the period of record of this study is shown on figure 8. A total of 27 samples were collected for water-quality analysis.

Feather River near Nicolaus

The Feather River near Nicolaus site (fig. 5, site 4) is located near the confluence of the Feather and Sacramento rivers. The Feather River is a large tributary to the Sacramento River. Flow in the lower Feather River is controlled mainly by releases from Lake Oroville, the second largest reservoir within the Sacramento River Basin, and by flow from a major tributary, the Yuba River. Levees have been constructed on the lower Feather River for flood control. Forest land is the major (about 78 percent of the total) land use or land cover (Anderson and others, 1976) for the Feather River Basin (fig. 9). Gold mining was also an important land use in the Sierra Nevada foothills part of the Feather River Basin, but cannot be detected by remote sensing and is not part of the Anderson and others (1976) classification. The location of gold mines is shown on figure 3. The Yuba and the Bear rivers both flow into the Feather River above the fixed site. Both the Yuba River and Bear River basins have been affected by past gold mining and are a source of mercury to the lower Feather and Sacramento rivers (May and others, 2000). A hydrograph for the period of record is shown on figure 9. A total of 27 samples were collected for water-quality analysis.







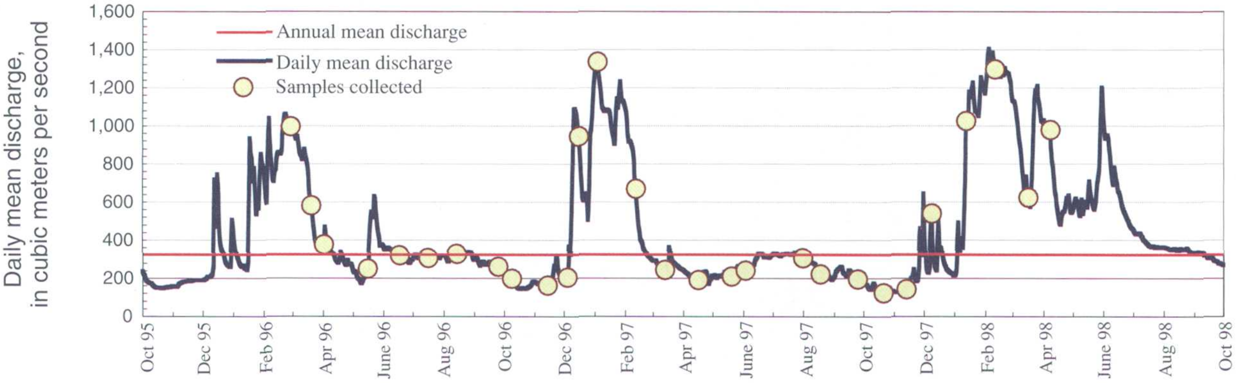


Figure 7. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Sacramento River at Colusa sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

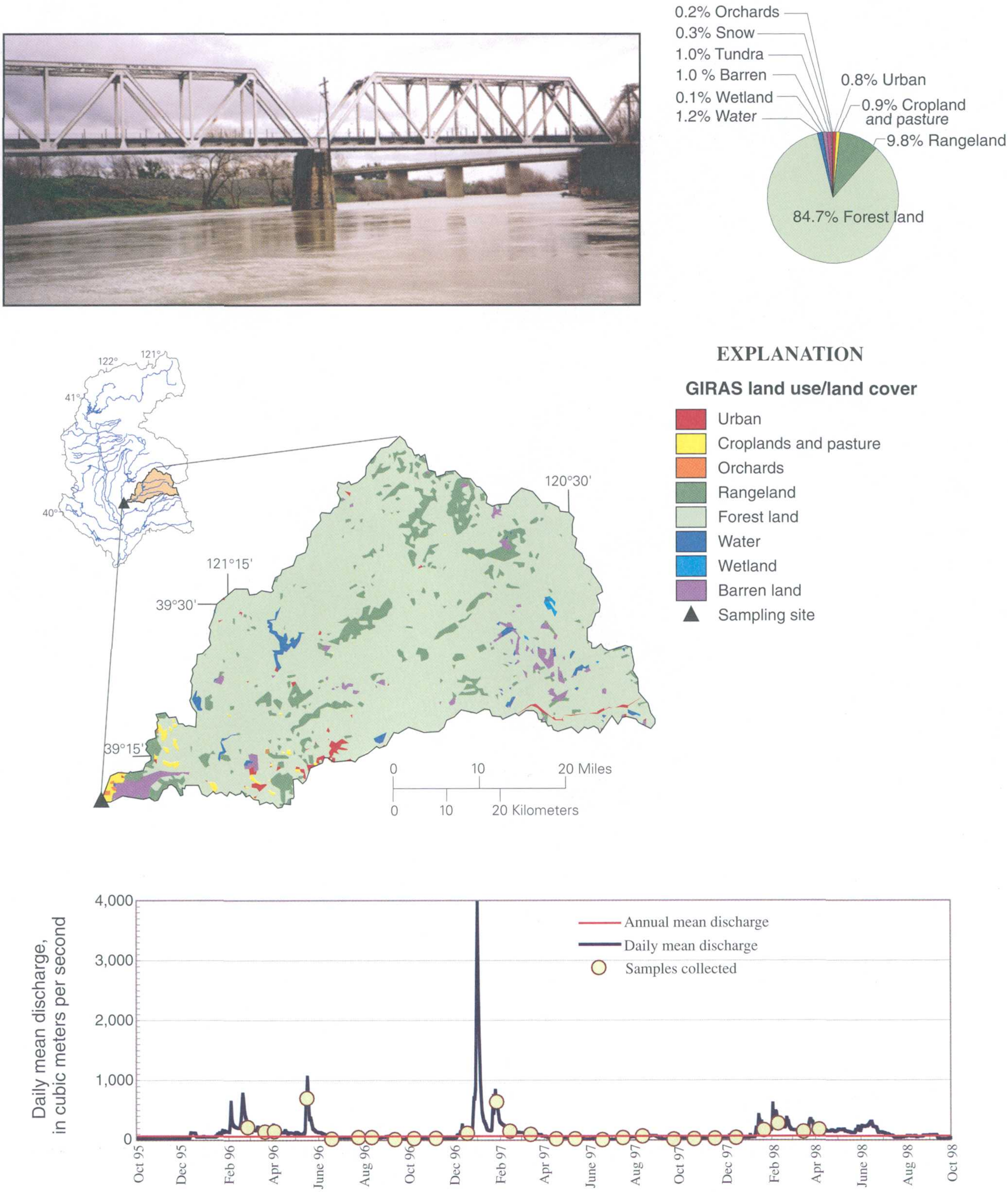


Figure 8. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Yuba River at Marysville sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

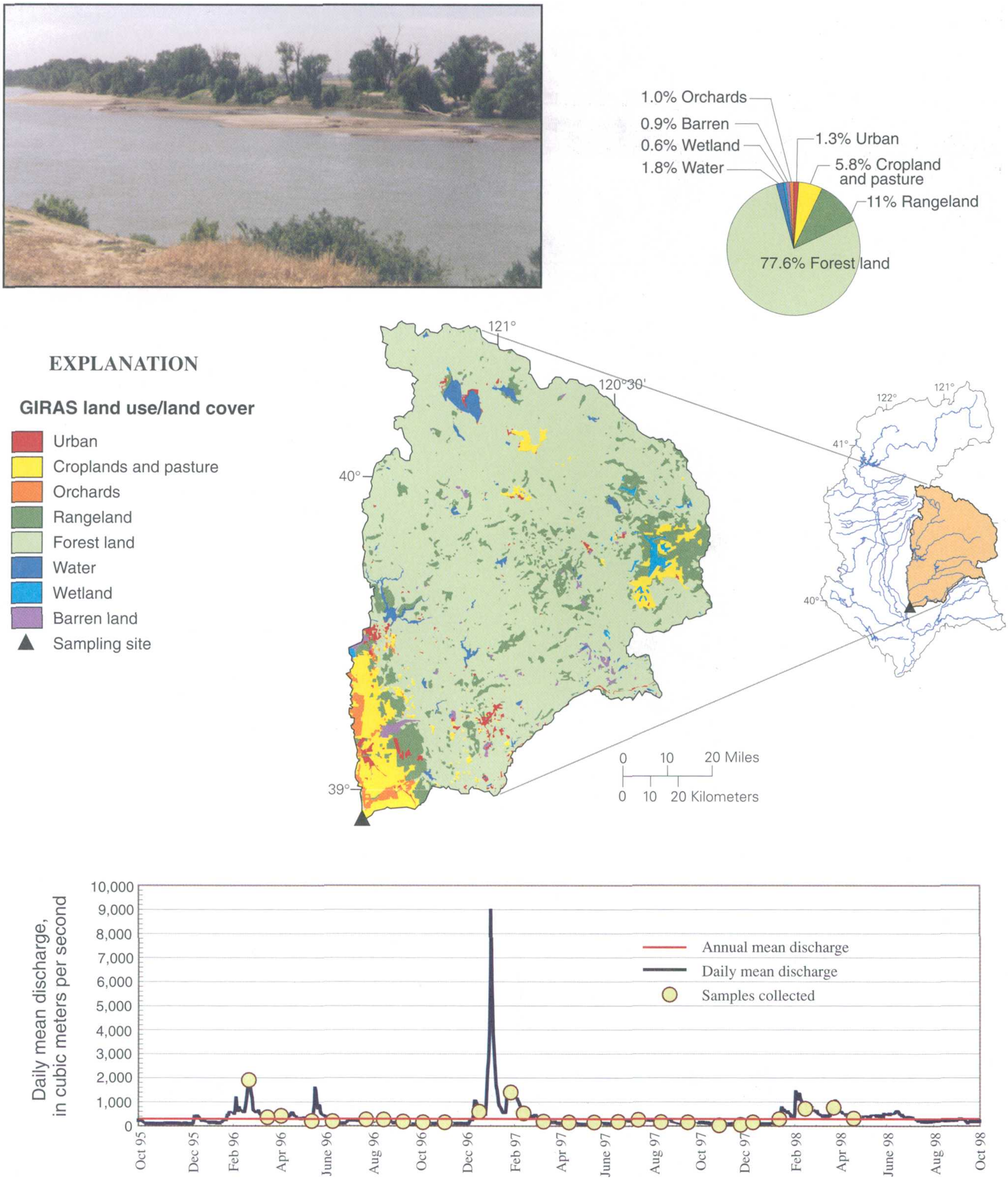


Figure 9. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Feather River near Nicolaus sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

Sacramento Slough near Knights Landing

The Sacramento Slough is part of a system of agricultural drainage and flood control for a large part of the eastern Sacramento Valley. The Sacramento Slough near Knights Landing site (fig. 5, site 5) is located just above the confluence with the Sacramento River and Sacramento Slough. The principal land use is cropland and pasture (about 54 percent of the total). Rice is the main crop of the cropland and pasture land-use area. A hydrograph for the period of record is shown on figure 10. A total of 25 samples were collected for water-quality analysis.

Colusa Basin Drain at Road 99E near Knights Landing

The Colusa Basin Drain is part of a system of agricultural and flood control drainage for a large part of the western side of the Sacramento Valley. The Colusa Basin Drain at Road 99E near Knights Landing site is located just above the confluence with the Sacramento River (fig. 5, site 6). Cropland and pasture and orchards, the principal land uses in this basin, constitute about 64 percent of the land use; rice is the main crop in this area. A hydrograph for the period of this study is shown on figure 11. A total of 31 samples were collected for water-quality analysis. Because a downstream dam affects water levels, continuous discharge could not be measured at this site. As a result, discharge from an upstream site are plotted on figure 11.

Sacramento River at Verona

The Sacramento River at Verona site (fig. 5, site 7) is located just downstream from the confluences of the Sacramento River with the Colusa Basin Drain, the Feather River, and the Sacramento Slough. The Sacramento River potentially can be affected by agricultural and mine drainage at the Verona site. Flow in the Sacramento River at this site depends on upstream conditions of the Sacramento and Feather rivers, and on the amount of agricultural drainage or stormwater runoff from the Colusa Basin Drain and Sacramento Slough. The flow is diverted out of the Sacramento River at Verona to the Yolo Bypass when the Sacramento River flow exceeds approximately 1,560 m^3/s. The land use for this basin is shown on figure 12. Forest land is the largest classification of land use or land cover at this site and constitutes about 62 percent of the total. A hydrograph for the period of record is shown on figure 12. A total of 28 samples were collected for water-quality analysis at this site.

Cache Creek at Rumsey

Cache Creek is the main stream draining Clear Lake, which is one of the few water bodies in the basin listed as impaired by nutrients (U.S. Environmental Protection Agency, accessed October 1, 1999). However, Cache Creek, which (as would be expected) is elevated in nutrients relative to others in this study, was selected because of the occurrence of mercury. Mercury was mined at several locations (fig. 3) in the Cache Creek Basin. The Cache Creek at Rumsey site (fig. 5, site 8) is located approximately midway between the outflow from Clear Lake and the point of drainage into the Yolo Bypass. Although the creek is not shown connected to the Sacramento River in figure 1, during the winter (when most of the yearly rainfall occurs) increases in flow in Cache Creek enter the Yolo Bypass, which ultimately reenters the Sacramento River.

The principal land uses in the basin are forest land (about 47 percent of the total) and rangeland (about 37 percent) (fig. 13). A hydrograph for the period of this study also is shown in figure 13. A total of 31 samples were collected for water-quality analysis.

Arcade Creek near Del Paso Heights

Arcade Creek was selected to determine the effects of an urban land-use area on water quality. The Arcade Creek near Del Paso Heights site (fig. 5, site 9) is located near the mouth of the drainage basin. The entire Arcade Creek Basin is located in the urbanized greater Sacramento metropolitan area. The Anderson land-use classification (Anderson and others, 1976) for this basin is mainly urban land, at about 79 percent of the total. The remote sensing data for these land-use classifications were collected in 1975. Since that time, approximately 100 percent of the Arcade Creek watershed has been urbanized. A hydrograph for the period of record for this site is shown on figure 14. A total of 43 samples were collected for water-quality analysis.

American River at Sacramento

The American River is a large tributary to the Sacramento River in the lower part of the basin. The

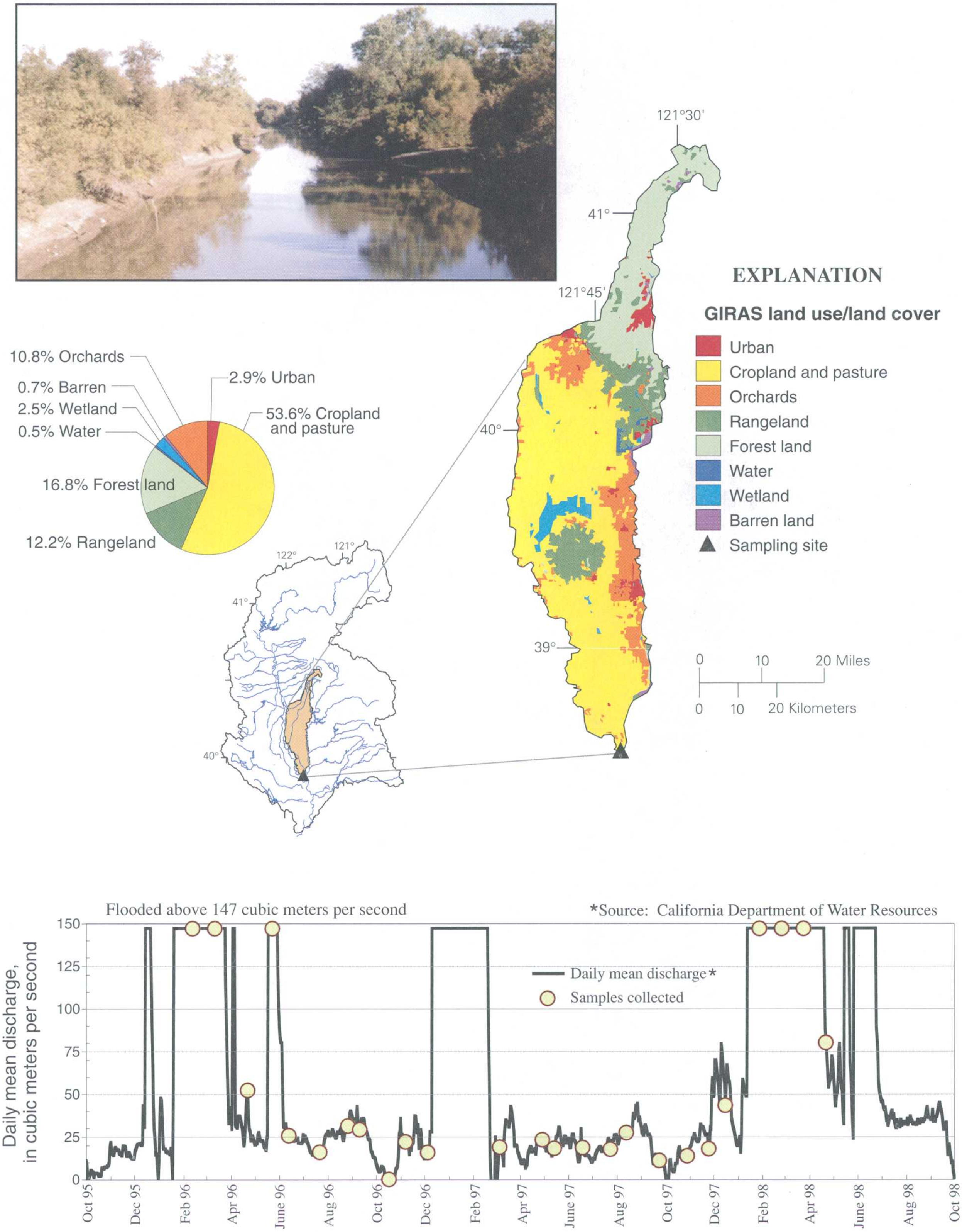
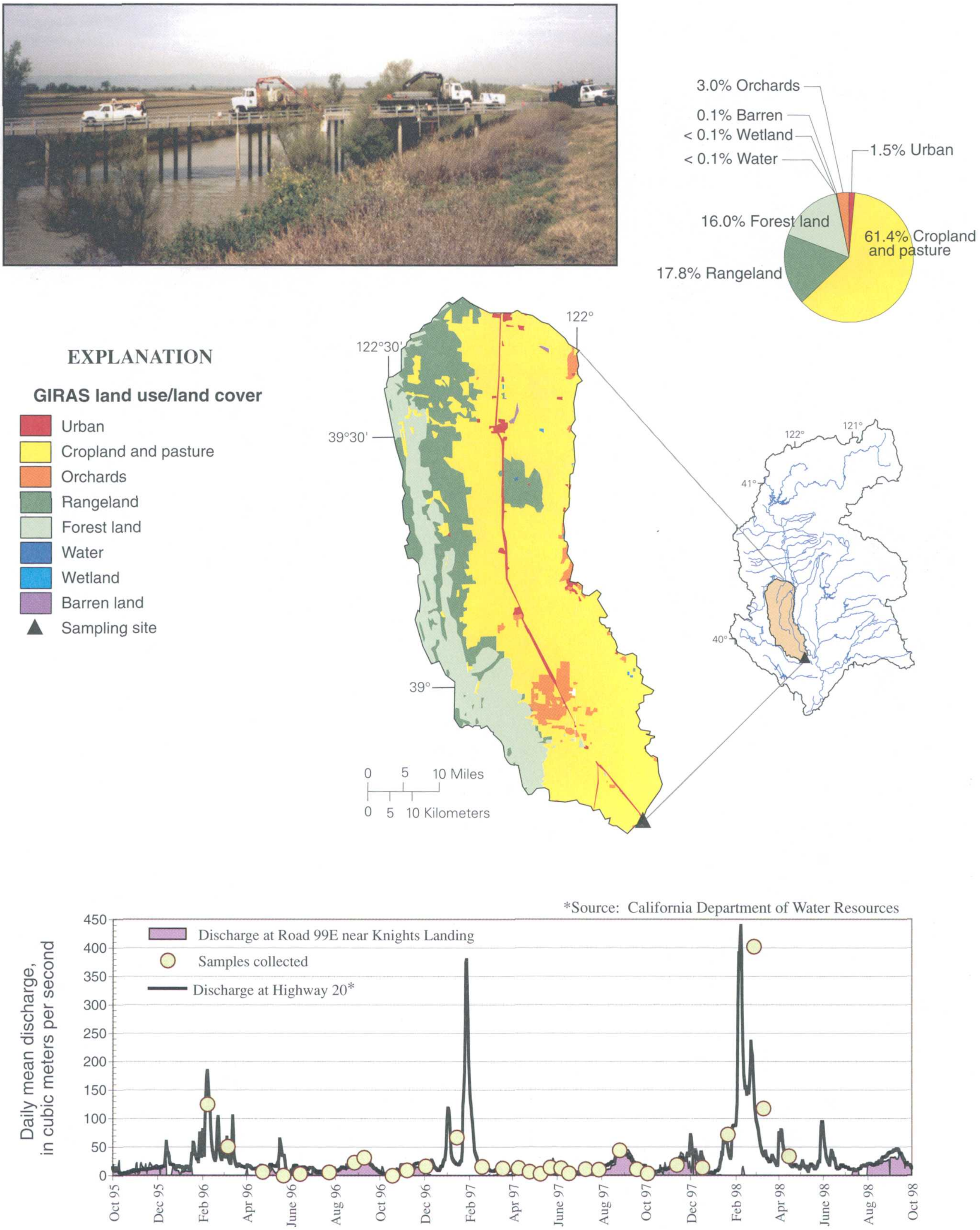


Figure 10. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Sacramento Slough near Knights Landing sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.



*Source: California Department of Water Resources

Figure 11. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Colusa Basin Drain at Road 99E near Knights Landing sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

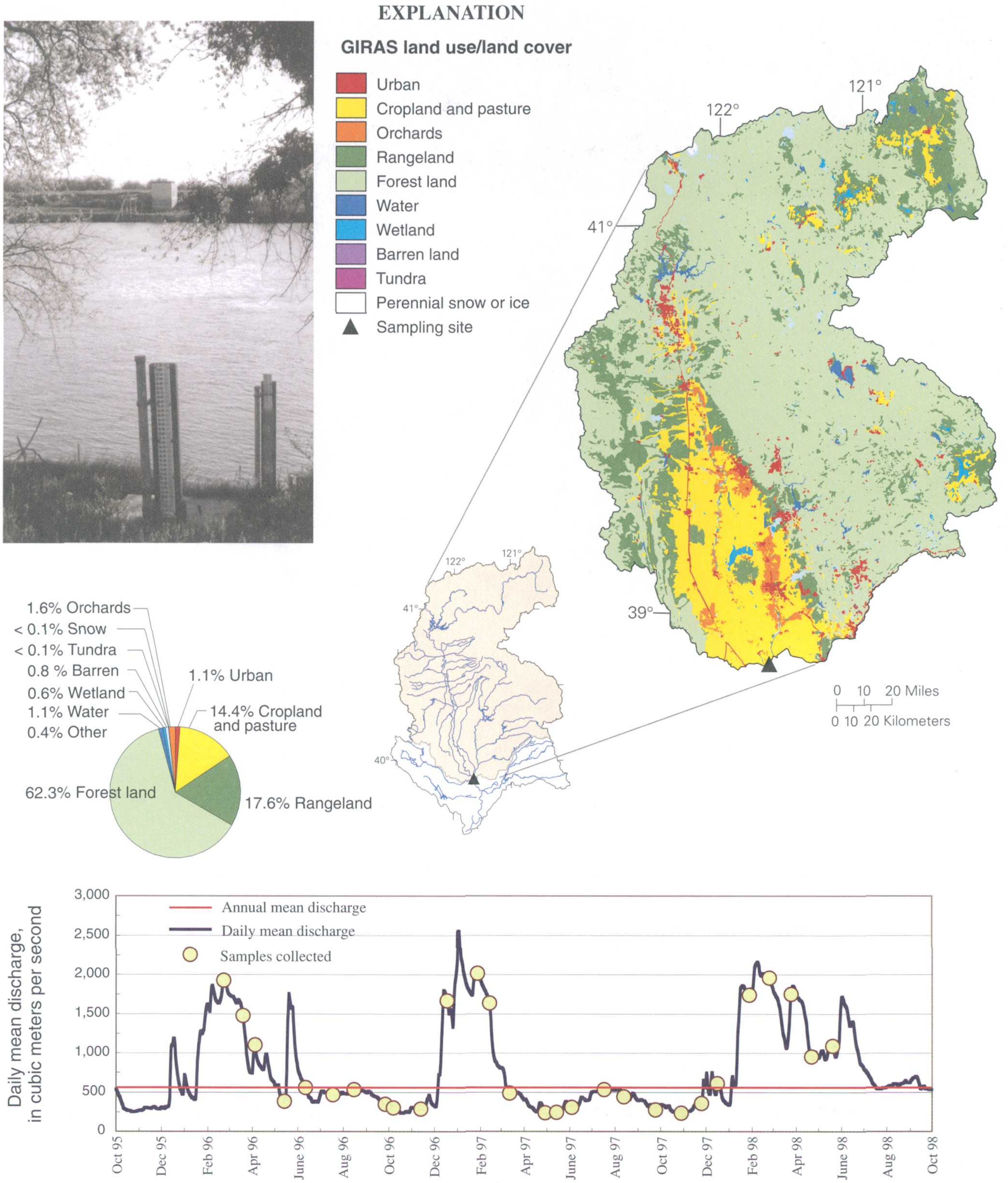


Figure 12. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Sacramento River at Verona sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

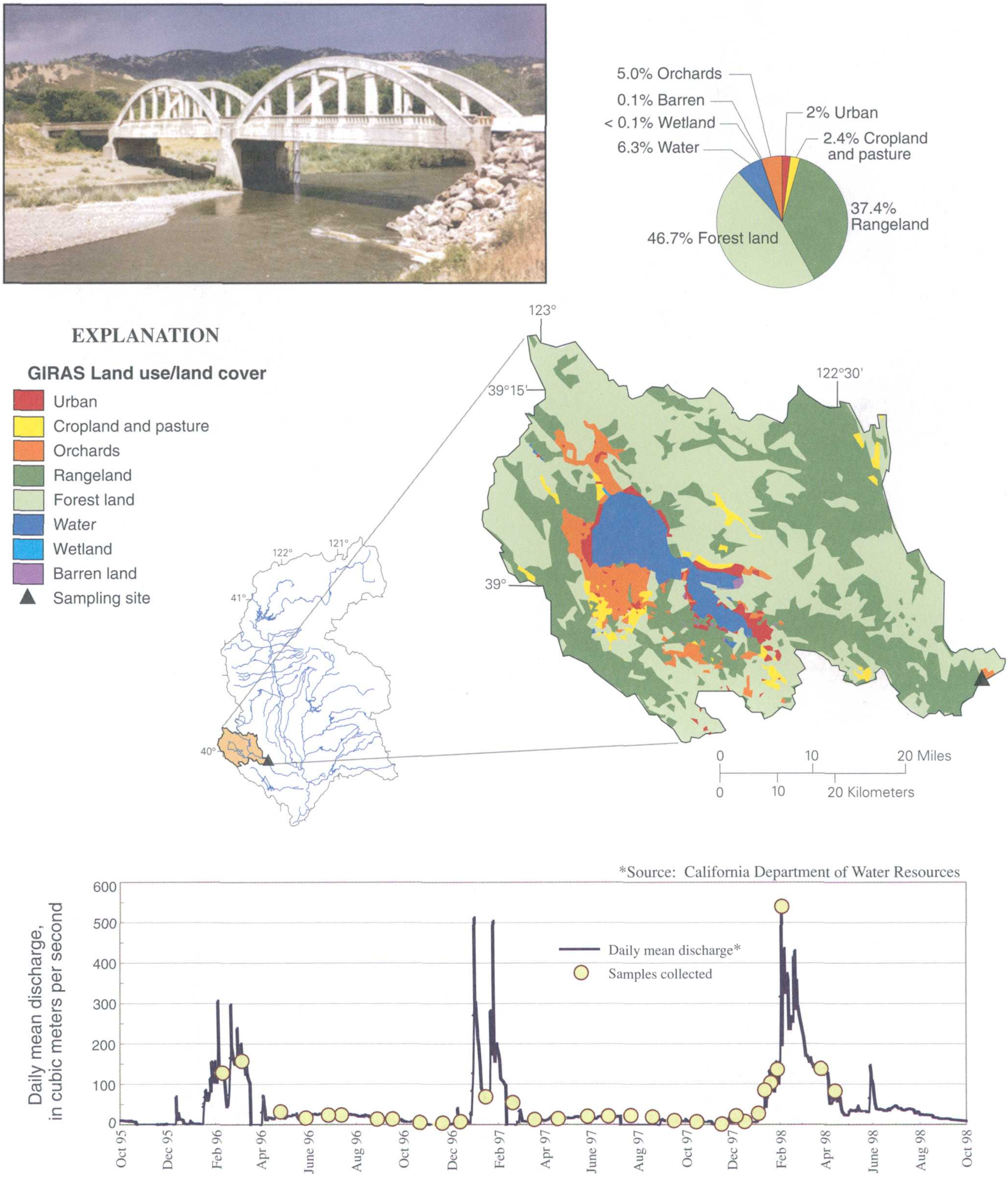
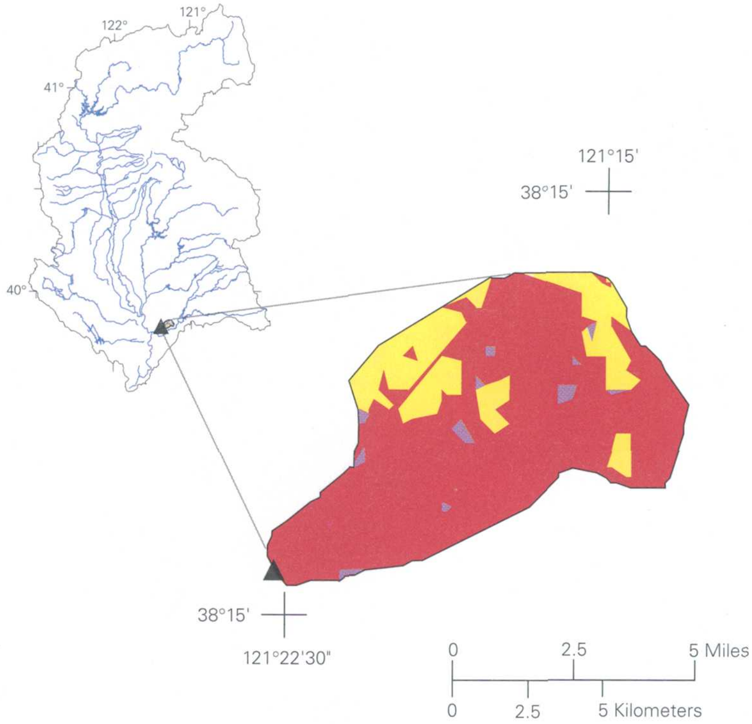
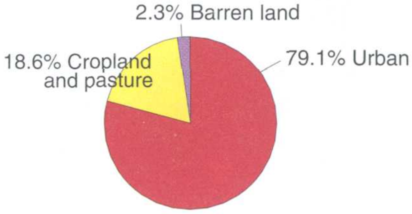


Figure 13. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Cache Creek at Rumsey sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.





EXPLANATION

GIRAS land use/land cover

- 🟥 Urban
- 🟨 Croplands and pasture
- 🟪 Barren land
- ▲ Sampling site

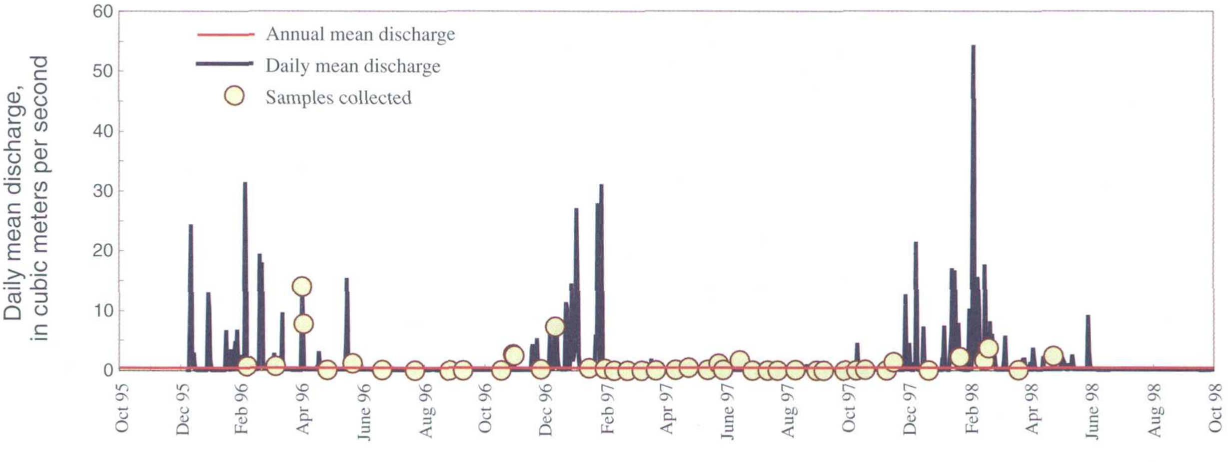


Figure 14. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Arcade Creek near Del Paso Heights sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

American River at Sacramento site (fig. 5, site 10) is located near the mouth of the river in the city of Sacramento. The Anderson land-use classification (Anderson and others, 1976) for the American River Basin is shown on figure 15. Forest land constitutes the greatest percentage of land use or land cover (about 77 percent). Gold mining also occurred within the American River Basin. Placer gold was first discovered in the American River in 1849, triggering the exploration and mining of gold that followed. The lower American River is listed as an impaired water body owing to mercury lost during gold recovery. A hydrograph for the period of record is shown on figure 15. A total of 27 samples were collected for water-quality analysis.

Sacramento River at Freeport

The Sacramento River at Freeport site (fig. 5, site 11) is the lowermost fixed site on the Sacramento River. Therefore, water-quality samples at this site integrate the effects of most land uses or land covers and physiographic provinces of the entire watershed. The Anderson land-use classification (Anderson and others, 1976) for this site is shown on figure 16. Forest land is the largest land-use category (about 63 percent). A hydrograph for the period of record is shown on figure 16. A total of 34 samples were collected for water-quality analysis.

Yolo Bypass at Interstate 80 near West Sacramento

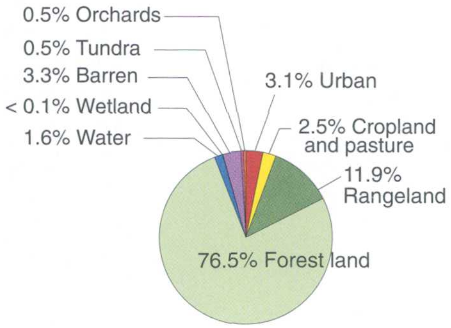
The Yolo Bypass is a distributary flood control channel of the Sacramento River. The Yolo Bypass at Interstate 80 near West Sacramento site is located near a gaging station just upstream from a bridge, which facilitates water sample collection. Flow at that station adequately represents flow at the water quality sampling site. Water from the Sacramento River is diverted at the Yolo Bypass at Interstate 80 near West Sacramento site (fig. 5, site 12) near Verona (fig. 1) when flow in the Sacramento River at that point exceeds 1,560 m^3/s. The Yolo Bypass has reduced the threat of flooding to downstream communities, including the city of Sacramento. Water enters the Yolo Bypass only in response to flood-control management; during relatively dry years, there is no flow. Because of the proximity of the Yolo Bypass to the Sacramento River at Freeport, both sites have similar land-use descriptions. A hydrograph for the period of record is shown on figure 17. High discharge was recorded during two winters of this NAWQA study. A major flood occurred in January 1997 as a result of a large tropical storm that produced high rainfall amounts in the Sierra Nevada. Rain fell on snow, and high discharges were recorded in the Feather, the Yuba, and the American river basins. During the winter of 1997–1998, El Niño conditions resulted in higher than normal precipitation over most of the Sacramento River Basin. A total of 10 samples were collected for water-quality analysis.

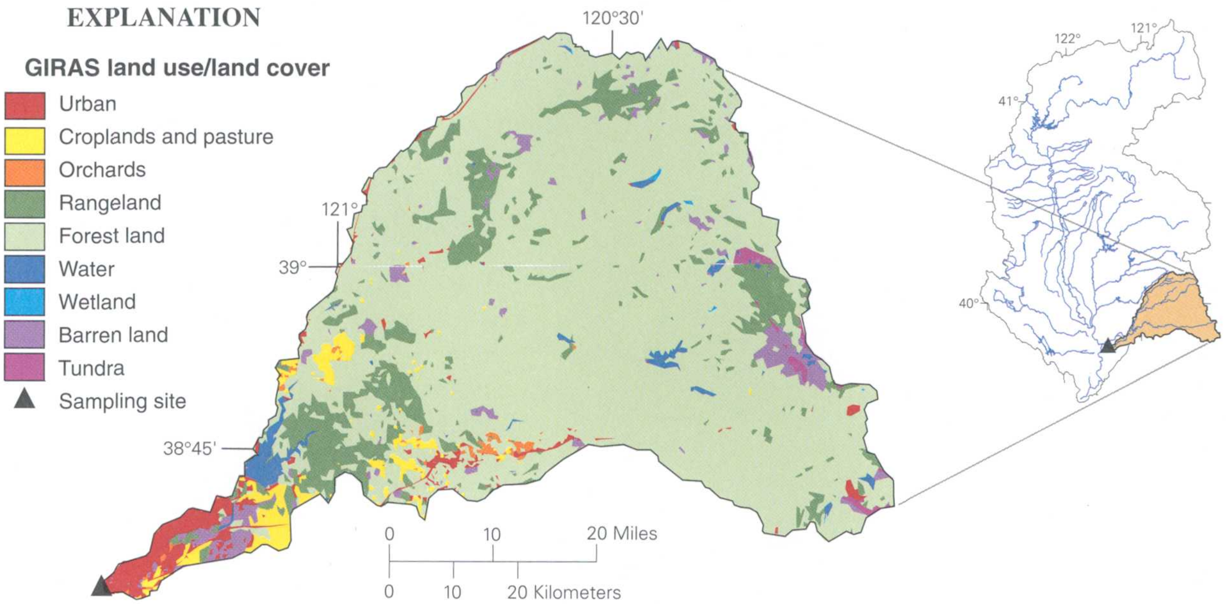
DATA COLLECTION

This section describes sampling methods and quality-control activities. As noted earlier in the report, data collection was from October 1995 to October 1998 at 12 fixed sites, of which 8 are integrator and 4 are indicator sites.

Sampling Methods

Constituents measured at the fixed sites and their detection limits are shown in table 4. Sampling methods for field-measured constituents and properties, major ions, nutrients, dissolved and suspended organic carbon, and suspended sediment conformed to guidelines specified for the NAWQA Program as documented by Shelton (1994). The methodology called for the use of Teflon sampling bottles and splitting equipment to minimize errors from contamination or other sampling artifacts. Water samples were collected from either bridges or boats using a procedure designed to collect a sample representative of the stream channel at each site. The equal-width-increment sampling method was used at most sites. This part of the sampling procedure has been described by Edwards and Glysson (1988) and Ward and Hair (1990). When appropriate, water was collected with an isokinetic sampling apparatus to ensure the collection of a representative sample for suspended sediment. The isokinetic sampling apparatus requires stream velocities in excess of 0.61 m/s. When the stream velocities were less, a weighted bottle was used to collect the sample. The deepest recommended sampling depth for this method is 4.6 m (Shelton, 1994). Water depths were in excess of 4.6 m at some sites, especially the Sacramento River Sites. In those cases, only the upper 4.6 m of water were sampled.





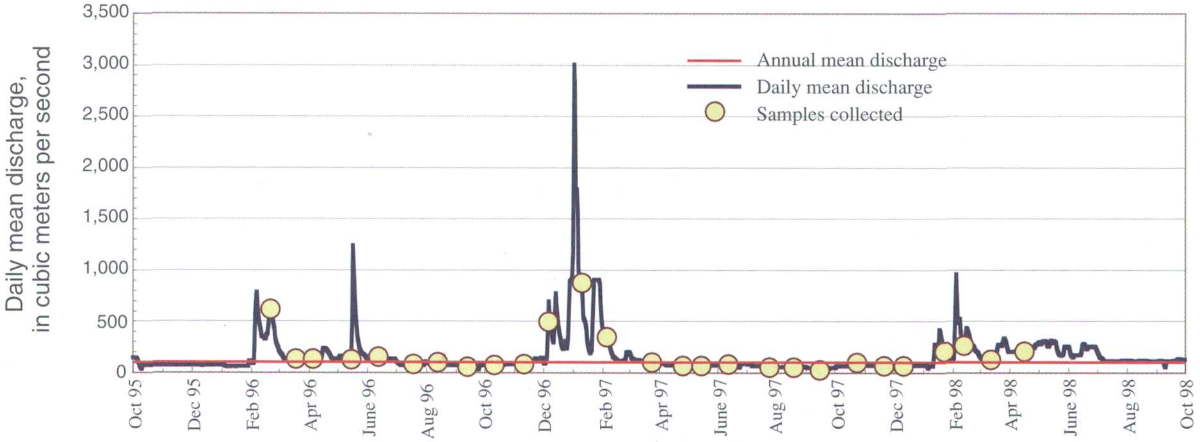


Figure 15. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the American River at Sacramento sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

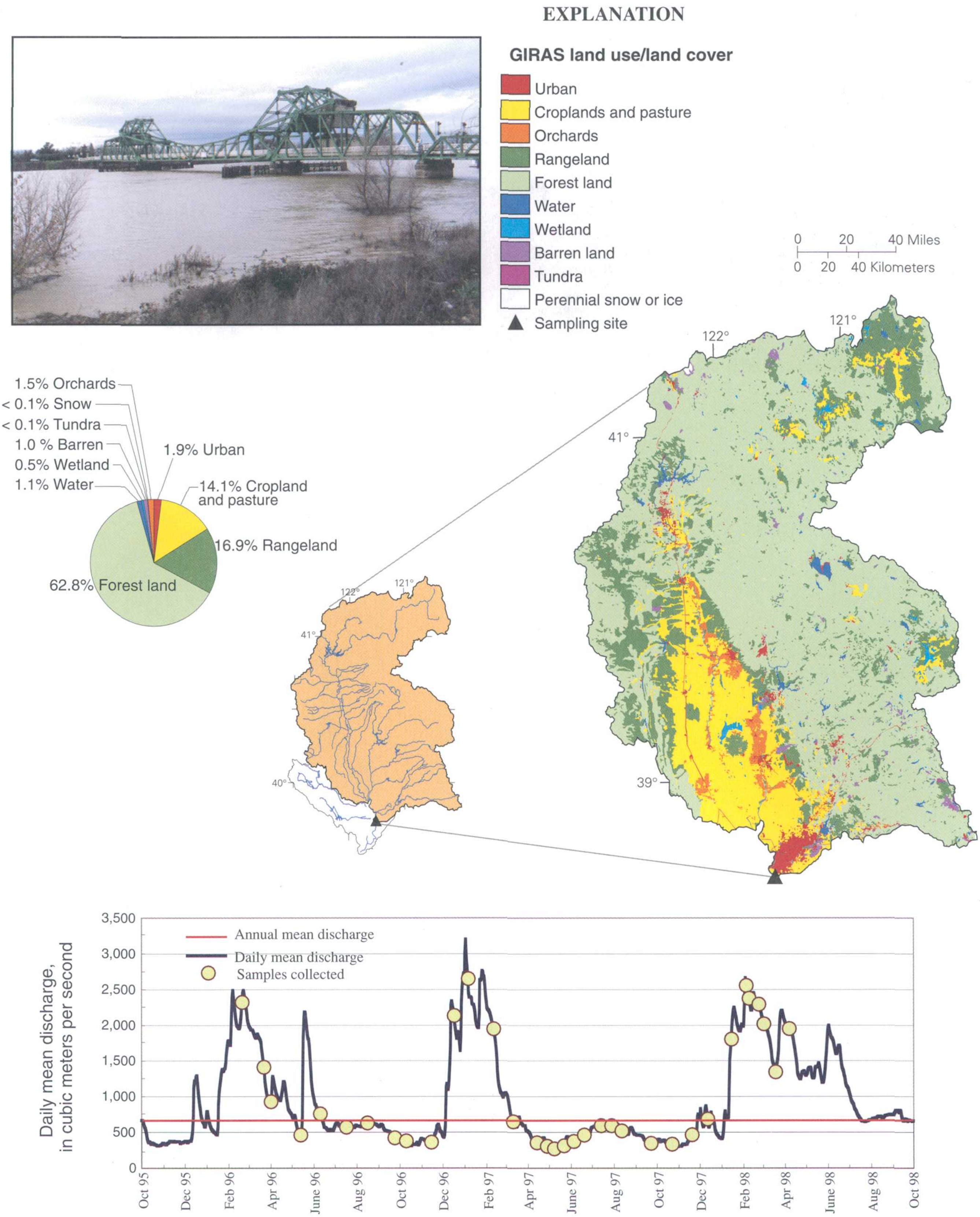


Figure 16. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Sacramento River at Freeport sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

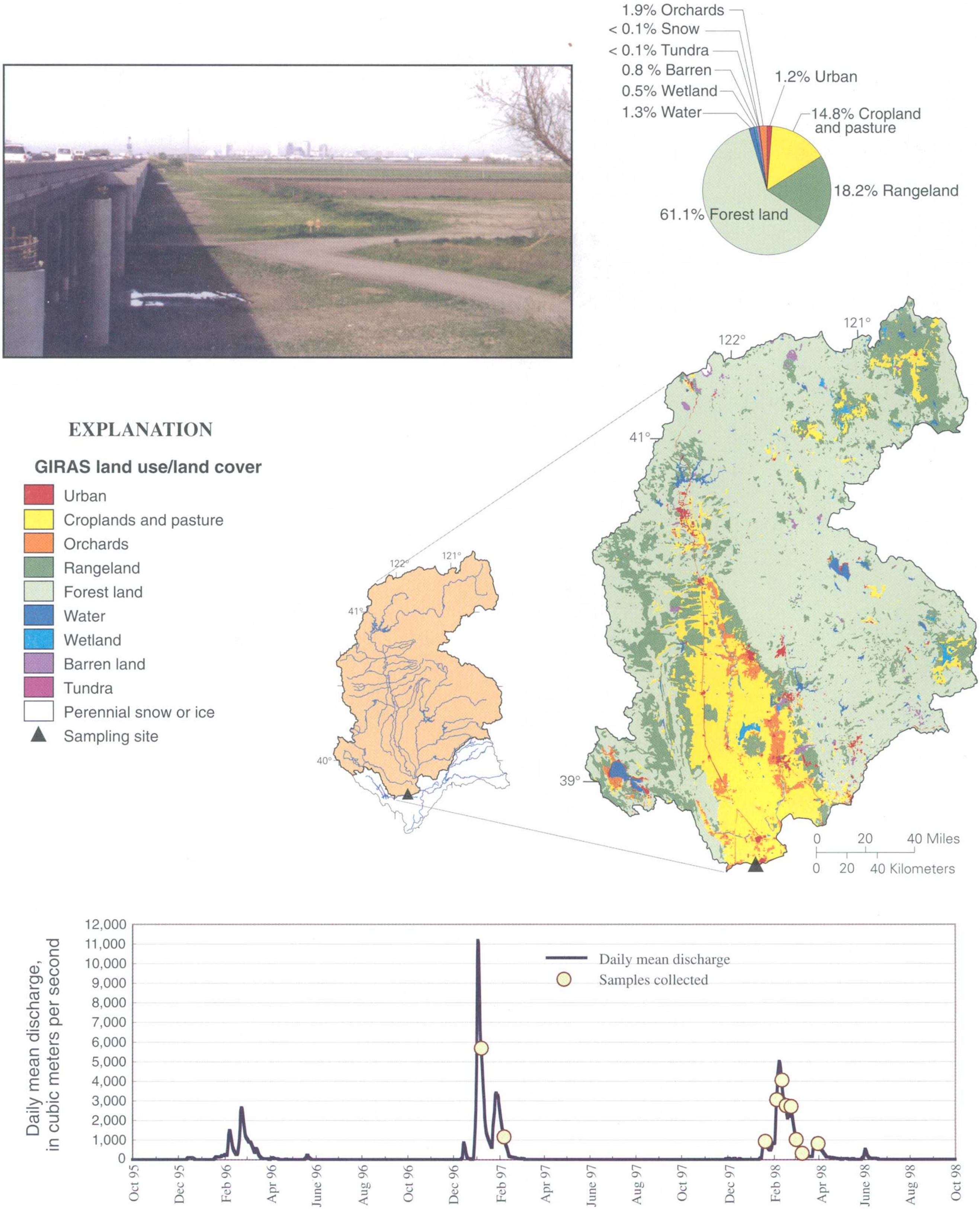


Figure 17. GIRAS land use/land cover, land use (in percent), drainage basin location, and mean daily discharge for the period of record for the Yolo Bypass at Interstate 80 near West Sacramento sampling site, California. Location of site is shown on figure 5. GIRAS data from Fegeas and others (1983). GIRAS, Geographic Information Retrieval and Analysis System.

Table 4. Water-quality constituents measured at the fixed sites and associated detection limits

[All constituents are in milligram per liter unless otherwise noted. µg/L, microgram per liter; ng/L, nanogram per liter]

Water-quality constituent	Detection limit
FIELD MEASUREMENTS	
Water temperature, degrees Celsius	None
Dissolved oxygen	0.1
Specific conductance, microsiemens per centimeter at 25°C	1
pH, units	0.1
Alkalinity	1
LABORATORY ANALYSES	
Suspended sediment	1
Total dissolved solids	1
Nutrients	
Total organic nitrogen plus ammonia	0.1
Dissolved organic nitrogen plus ammonia	0.2
Ammonia	0.015
Nitrite	0.01
Nitrite plus nitrate	0.05
Total phosphorus	0.01
Dissolved phosphorus	0.01
Orthophosphate	0.01
Organic carbon	
Dissolved organic carbon	0.1
Particulate organic carbon	0.2
Major ions	
Calcium	0.02
Chloride	0.1
Fluoride	0.1
Iron	10 µg/L
Magnesium	0.01
Potassium	0.1
Silica	0.01
Sodium	0.2
Sulfate	0.1
Trace elements (other than mercury)	
Aluminum	1 µg/L
Antimony	1 µg/L
Arsenic	1 µg/L
Barium	1 µg/L
Beryllium	1 µg/L
Cadmium	1 µg/L
Chromium	1 µg/L
Cobalt	1 µg/L
Copper	1 µg/L
Lead	1 µg/L
Manganese	1 µg/L
Molybdenum	1 µg/L
Nickel	1 µg/L
Selenium	1 µg/L
Silver	1 µg/L
Uranium	1 µg/L
Zinc	1 µg/L
Mercury species	
Total mercury in unfiltered water	0.03 ng/L
Total methylmercury in unfiltered water	0.02 ng/L

The samples were then split equally with a Teflon cone splitter (Capel and others, 1995). Some water quality constituents—dissolved organic carbon, total mercury, and methylmercury—required special sampling procedures.

Dissolved and suspended organic carbon samples were collected separately with a dedicated Teflon sampling bottle at a single vertical at the center of the stream or the part of the stream with the greatest discharge. Water was sampled from the surface to the deepest part of the channel accessible with the isokinetic sampler. A separate sample was collected to avoid any potential contamination of the dissolved organic carbon sample. For some of the sample-collection equipment, such as Teflon bottles and the cone splitter, a methanol rinse was included as part of the washing procedure. Because residual methanol might have contaminated the dissolved organic carbon samples, those samples were collected separately with a dedicated Teflon bottle. Another sampling exception was for the mercury and methylmercury in unfiltered water samples. A dedicated 3-L Teflon bottle was used to collect those samples. Samples for mercury and methylmercury in unfiltered water also were collected from a single vertical near the center of the channel or the part of the stream with the greatest discharge. The 3-L Teflon bottle and the Teflon bottles used to hold the mercury and methylmercury in unfiltered water samples were cleaned by soaking in 10-percent hydrochloric acid at 65°C for 48 hours prior to sampling. The Teflon bottles were filled with 1-percent hydrochloric acid for transport to the field site, and the bottle caps were wrench-tightened to avoid contamination from atmospheric mercury. Because the cleaning procedure for the mercury 3-L Teflon bottle was compatible for dissolved and suspended organic carbon samples, the same bottle was used for each type of sample.

A 0.45-µm capsule filter was used to obtain filtered samples for alkalinity, major ions, nutrients, and trace metals. Dissolved organic carbon and suspended organic carbon samples were filtered with a 0.45-µm silver filter. Filtration was completed in the field inside a mobile laboratory following the sample-splitting procedure. Clean conditions were maintained for splitting, filtration, and preservation (when necessary) by the use of frame-mounted chamber bags to eliminate sampling artifacts caused by dust. All samples, except the mercury and methylmercury samples, were then placed on ice and shipped to the USGS National Water Quality Laboratory in Lakewood, Colo.

Analyses of pH, specific conductance, and alkalinity were completed in the field immediately after sample collection and splitting according to the procedures described by Shelton (1994). Temperature and dissolved oxygen were measured at a point in the central part of the stream or in that part of the stream with maximum flow. Samples for major ions and nutrients were analyzed according to the methods of Fishman and Friedman (1989) and Fishman (1993). Trace metals (not including mercury and methylmercury in unfiltered water) were analyzed by inductively coupled plasma mass spectrometry according to the method of Faires (1993) and Jones and Garbarino (1999). Samples for dissolved and suspended organic carbon were analyzed by the method of Brenton and Arnett (1993). Mercury in unfiltered water was analyzed by the method of Bloom and Fitzgerald (1987); in this method, bromine monochloride oxidation, two-stage gold amalgamation, and cold-vapor atomic fluorescence detection are used to achieve a detection limit of 0.03 ng/L. Methylmercury in unfiltered water was analyzed by the method of Horvat and others (1993) and Liang and others (1993); this method utilizes a distillation and ethylation process to remove methylmercury from interfering substances and achieves a detection limit of 0.02 ng/L. The mercury and methylmercury samples were analyzed by the USGS Mercury Research Laboratory in Madison, Wis.

Quality Control

The design of the quality control program for surface-water sampling of the NAWQA Program has been described by Mueller and others (1997). The quality control samples collected for inorganic constituents, and dissolved and suspended organic carbon, consisted of field blanks and replicate samples. Quality control samples are collected to evaluate sampling bias and variability for surface-water chemical analyses owing to (1) the extent to which sampling methods and equipment introduce contaminants (positive bias) into water samples and (2) the extent to which sample collection, processing, and analysis affect the variability of measured constituent concentrations. Quality control samples for the fixed-site monitoring consisted of blank samples and replicate samples. The results of the quality control monitoring will be described in detail in a separate report. The results of the blank analyses showed that no systematic bias from contamination affected the data discussed in this report. The results of the replicate analyses showed that reproducibility was acceptable, and consistent with the precision described for the analytical methods, for all analyses.

DESCRIPTION OF WATER QUALITY DURING 1996–1998

This section presents a description of water quality with respect to inorganic and gross organic constituents.

Field Measurements

Boxplots of water temperature, dissolved oxygen saturation, specific conductance, pH, and alkalinity shown on figure 18 are based on data collected during 1996–1998. The site with the smallest annual range in temperature is the Sacramento River above Bend Bridge near Red Bluff. Because water is in the Yolo Bypass only during high flows, which generally occur in the winter, the boxplot for the Yolo Bypass at Interstate 80 near West Sacramento reflects relatively cooler temperatures. All other sites show a considerable range in temperature; the two agricultural sites, Sacramento Slough near Knights Landing and Colusa Basin Drain at Road 99E near Knights Landing, have the largest range and the highest temperatures. The highest temperatures at those sites can be attributed to the major agricultural land use, rice cultivation, in those two basins. Rice farming requires that fields remain flooded throughout the growing season (May through September). In past years, farmers operated the fields as flow-through systems. However, concern about the levels of rice herbicides and insecticides in the agricultural drains and the Sacramento River prompted changes in management practices. During 1996–1998, water was allowed to remain on a field for approximately 1 month before it was discharged to a drain. During this 1-month period, the water temperature increased. The measured water temperatures were highest for the Sacramento Slough and Colusa Basin Drain, which flow into the Sacramento River at a location near the site on the Sacramento River at Verona. However, the effect on the Sacramento River temperature is only slight because the discharge of these combined sites represents less than 10 percent of the flow of the Sacramento River. The median temperature of the Sacramento River at Verona (14.3°C) is similar to that of the Sacramento River at Colusa (13.6°C).

As mentioned, the lowest water temperatures for the mainstem Sacramento River were measured at the site above Bend Bridge near Red Bluff (fig. 18*A*). Temperatures rise downstream to the Freeport site, appreciably between Bend Bridge and Colusa (fig. 19). The rise between the Bend Bridge and Colusa sites probably is related to water transfers out of the Sacramento River, resulting in lower flow in the river. A diversion dam near Red Bluff, located just below the site above Bend Bridge near Red Bluff, supplies water to the Tehama Colusa Canal for irrigation. The Sacramento River between Keswick Dam and the sampling site above Bend Bridge near Red Bluff is managed (releases from Shasta Lake) to maintain the river temperature at or below 13.3°C

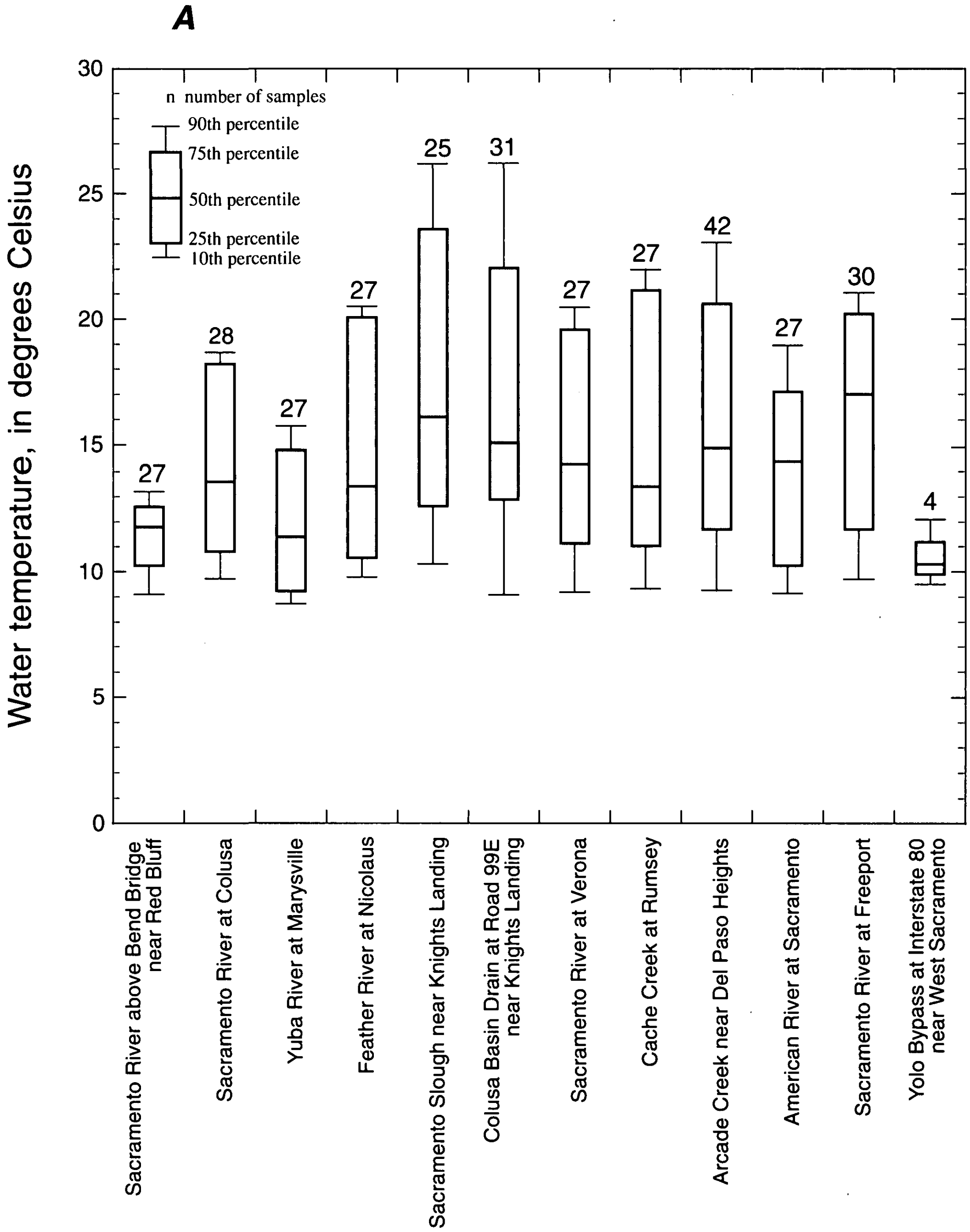


Figure 18. Boxplots of sampling sites in the Sacramento River Basin, California: (*A*) Water temperature. (*B*) Dissolved oxygen. (*C*) Specific conductance. (*D*) pH. (*E*) Alkalinity. On boxes with no visible 50th percentile mark, the 50th percentile falls on the 25th percentile.

during the critical migrating seasons of Chinook salmon and steelhead (U.S. Fish and Wildlife Service, 1995). As seen on figure 19, the river temperatures between these sites were maintained at or below the targeted temperature for the period of this study. The critical water temperatures can be maintained when sufficient water is present in the reservoirs but can be more difficult to maintain during periods of extended drought.

Dissolved oxygen concentrations were at or near saturation for all of the mainstem Sacramento River and the major tributaries (fig. 18*B*). Sags in dissolved oxygen content occurred at the agricultural sites—Sacramento Slough near Knights Landing and the Colusa Basin Drain at Road 99E near Knights Landing. The lowest median dissolved-oxygen saturation was recorded for the urban site at Arcade Creek near Del Paso Heights. The highest median dissolved-oxygen saturation was measured for the Cache Creek at Rumsey site. Cache Creek flows out of Clear Lake, which is on the California list of impaired water bodies for nutrients (table 1). Elevated levels of

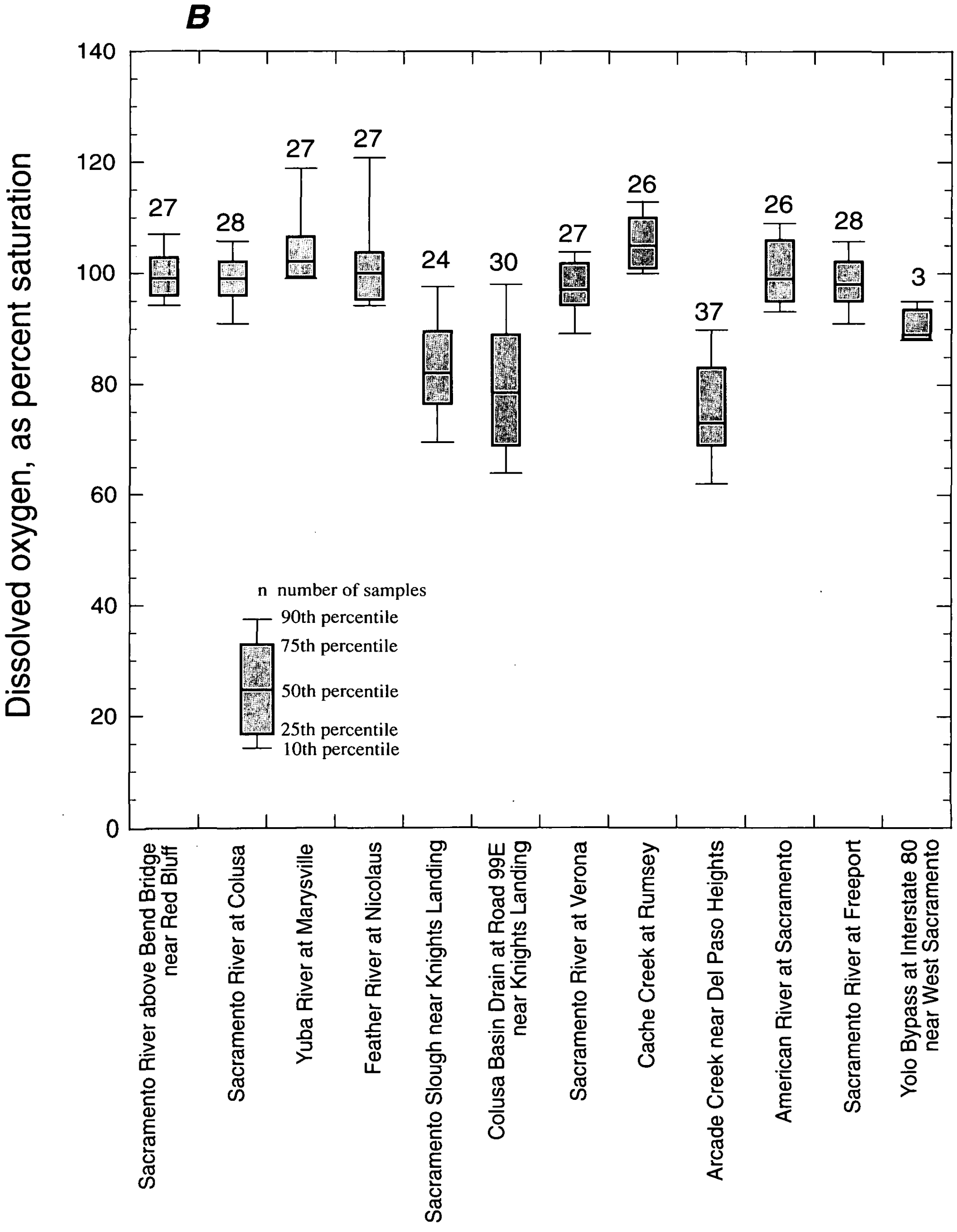


Figure 18.—*Continued.*

nutrients and (or) algae that may be present in Clear Lake would be transported to Cache Creek. Excess algal growth is probably responsible for these higher dissolved oxygen concentrations.

Specific conductance on the Sacramento River and the major eastern tributaries is generally low, with median values less than 150 µS/cm (fig. 18*C*). The two lowest median specific conductances were recorded for the American River at Sacramento (50 µS/cm) and the Yuba River at Marysville (70 µS/cm) sites. Specific conductance of the mainstem Sacramento River water tends to increase downstream from the site above Bend Bridge near Red Bluff to the site at Verona, but then slightly decreases at the site at Freeport. The decrease at Freeport can be attributed to dilution of water from the American River. The highest specific conductance values were recorded at the Colusa Basin Drain at Road 99E near Knights Landing and the Cache Creek at Rumsey sites. These two sites tend to have higher specific conductance in comparison with other streams in this study. This may be due to naturally higher amounts of dissolved solids in water that drains the Coast Ranges relative to other physiographic regions or may be partly due to land-use activities. Water released from rice fields within the Colusa Basin Drain basin has undergone some amount of evaporation, which would lead to higher specific conductance.

pH generally was similar at all sites, mostly ranging between 7 and 8 (fig.18*D*). The highest pH values were at the Cache Creek at Rumsey site. These values, similar to the higher dissolved oxygen

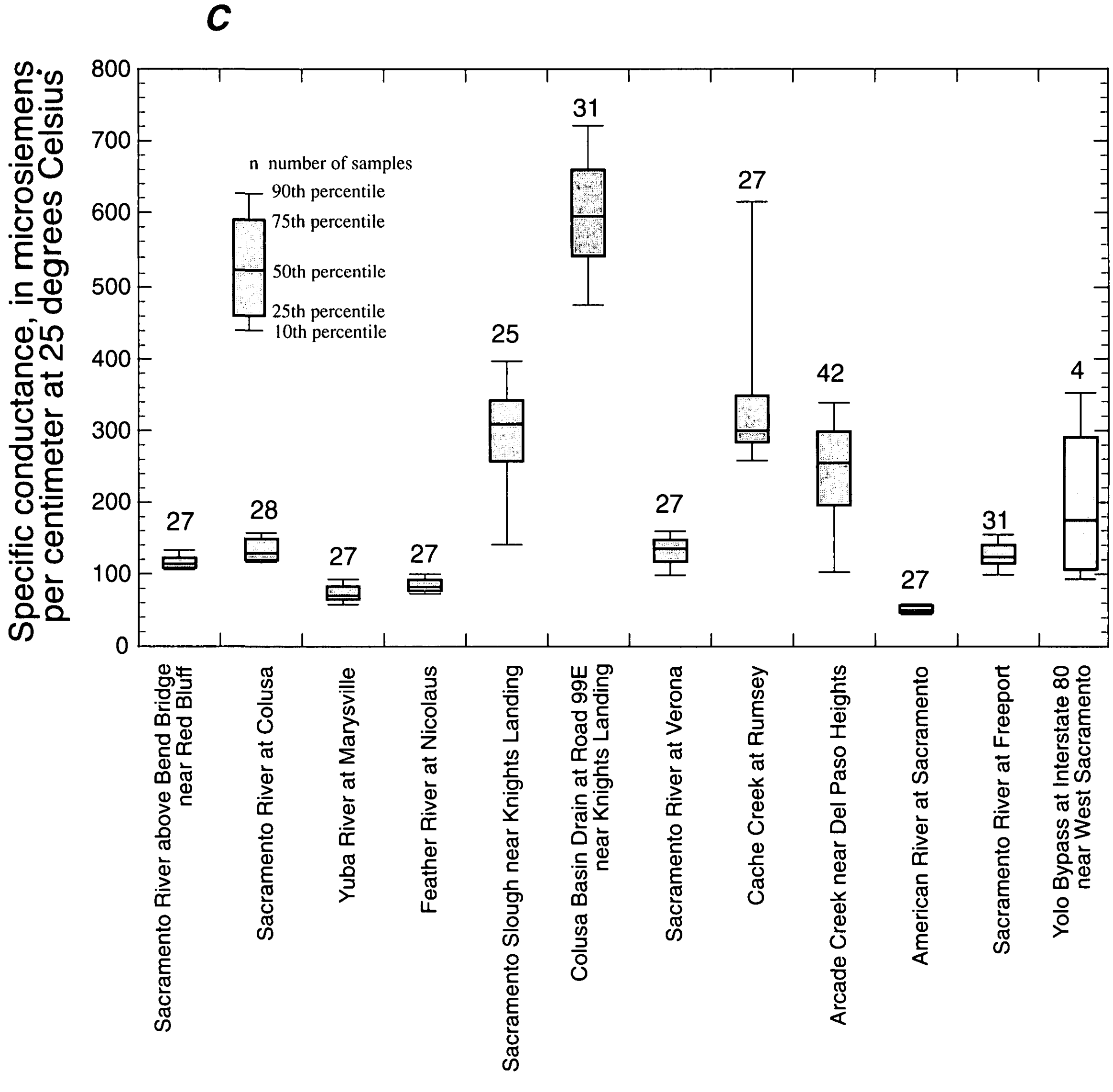


Figure 18.—*Continued.*

saturations at this site (fig. 18*B*), can be attributed to algae. Algal photosynthesis removes carbon dioxide from water, increasing pH.

Alkalinity of Sacramento River water was similar at all sites. Slight increases were noted downstream from the site above Bend Bridge near Red Bluff (fig. 18*E*), and alkalinity at the Freeport site was slightly less than that at the Verona site owing to dilution from the American River. The lowest measured alkalinities, similar to the lowest conductivities, were from the large eastern tributary sites of the Sierra Nevada physiographic province—the Yuba River near Marysville, the Feather River near Nicolaus, and the American River at Sacramento—owing to the lower dissolved solids in water that drains the Sierra Nevada. The highest alkalinities were from the agricultural sites of the Central Valley (Colusa Basin Drain at Road 99E near Knights Landing and Sacramento Slough near Knights Landing) and the Coast Ranges physiographic province, Cache Creek at Rumsey.

Suspended Sediment

Boxplots of suspended sediment are shown on figure 20. The highest median concentrations, for the period of record, were recorded for the two

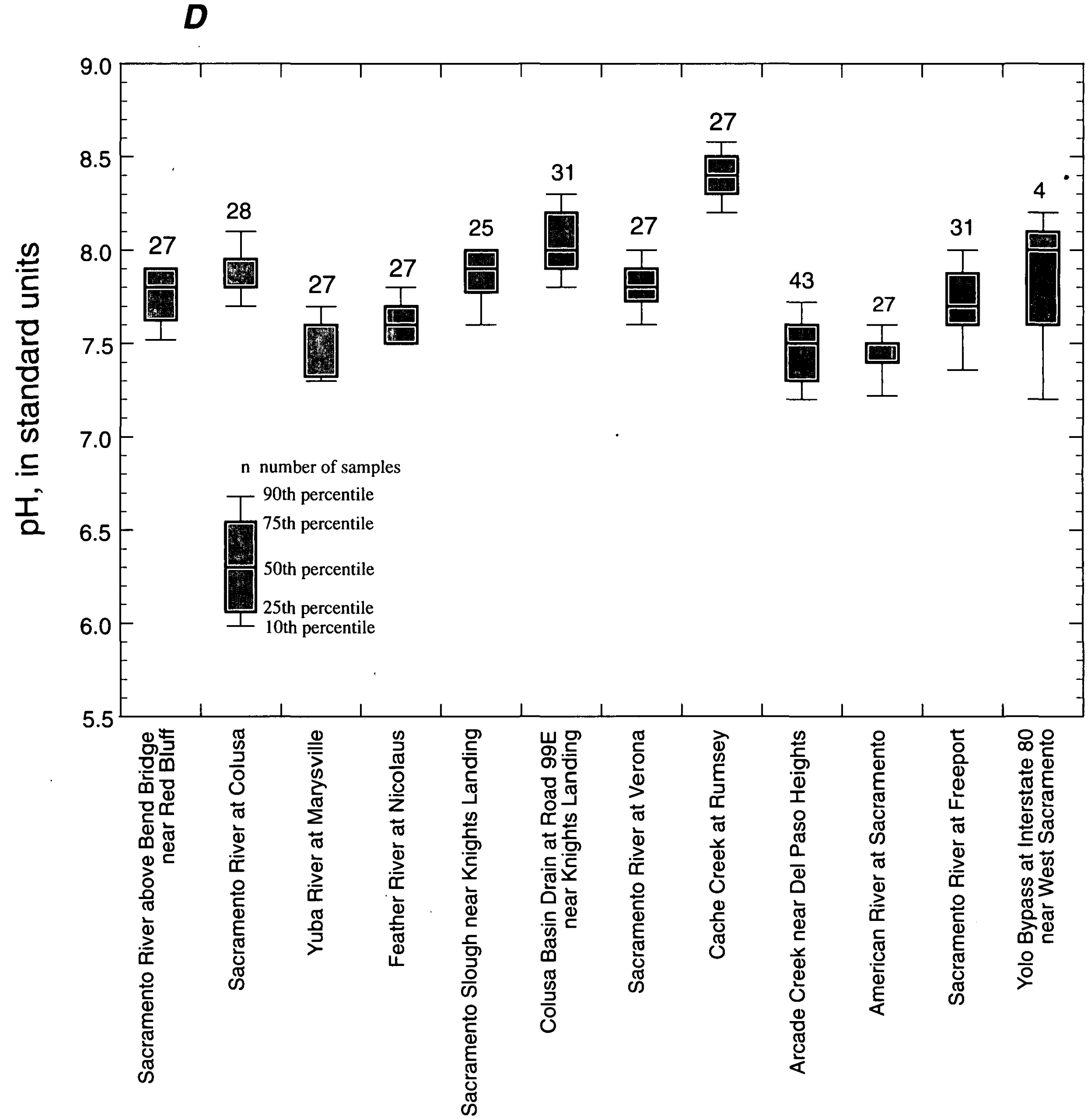


Figure 18.—*Continued.*

agricultural sites—the Sacramento Slough near Knights Landing and the Colusa Basin Drain at Road 99E near Knights Landing—and the Yolo Bypass at Interstate 80 near West Sacramento site. The concentrations for Yolo Bypass at Interstate 80 near West Sacramento are for the winter high-flow period. The greatest range in concentration and the highest concentration were measured at the Cache Creek at Rumsey site. The higher concentrations in Cache Creek were measured during the winter, especially during storm runoff. Suspended-sediment concentrations for Yolo Bypass at Interstate 80 near West Sacramento also are high because the water in that channel is mainly storm runoff.

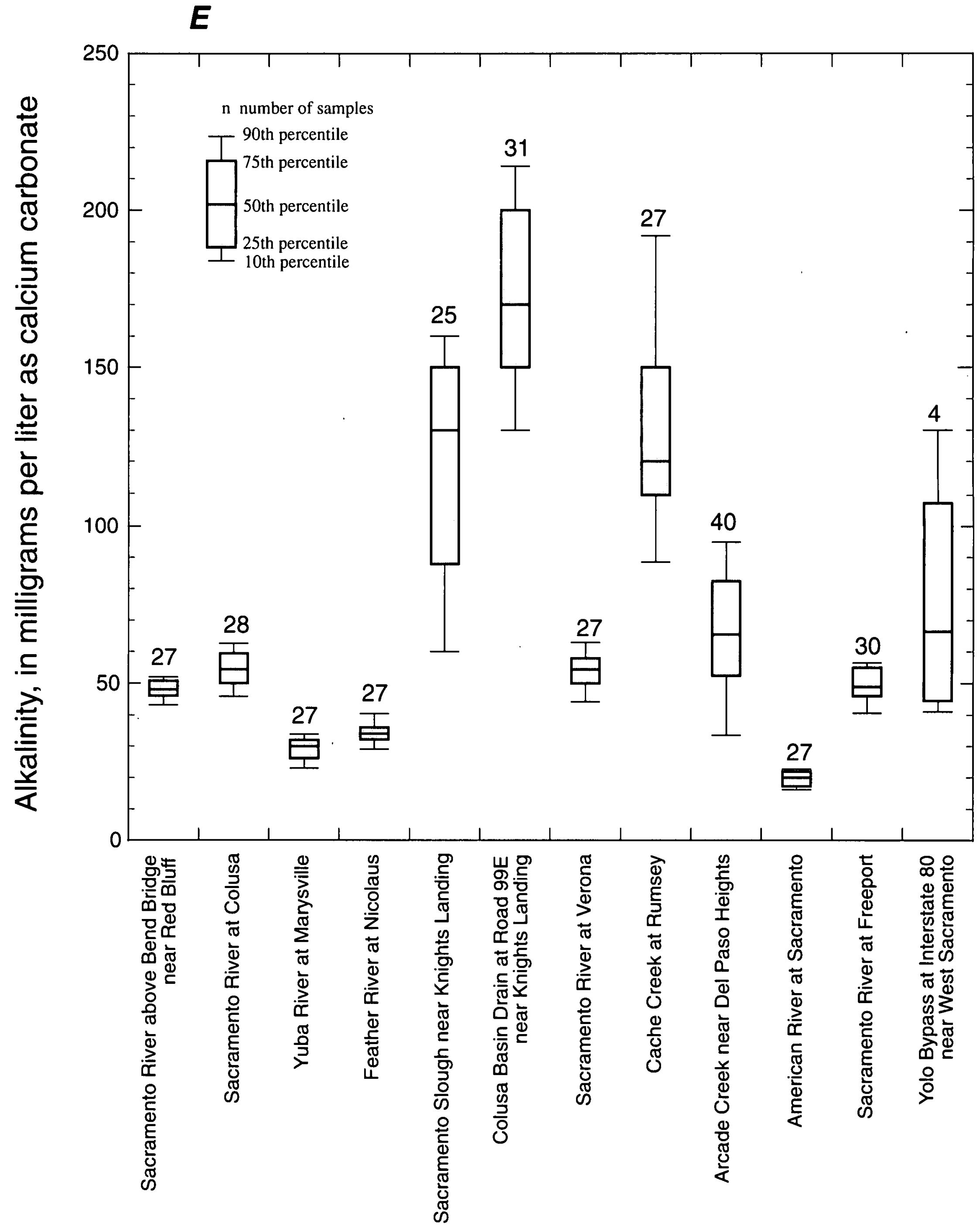


Figure 18.—*Continued.*

Nutrients and Dissolved Organic Carbon

Boxplots of nitrite plus nitrate for the fixed sites are shown on figure 21. The highest median concentration, 0.54 mg/L, was recorded at the urban site, Arcade Creek near Del Paso Heights, which could be attributed to nitrate from lawn and garden fertilizer. Although the agricultural land use in the Colusa Basin Drain and Sacramento Slough basins is similar—rice is the major crop—median concentrations of nitrite and nitrate were higher for the Colusa Basin Drain at Road 99E near Knights Landing site than for the Sacramento Slough near Knights Landing site. The lower nitrite plus nitrate for the Sacramento Slough site might be due to dilution from Butte Creek. Butte Creek originates from the Sierra Nevada and Middle Cascade Mountains where nutrient concentrations are expected to be low. Although no nutrient concentrations were collected in upper Butte Creek, concentrations in nearby streams of similar land use or land cover, such as Deer Creek or Big Chico Creek, have low nutrient concentrations (Domagalski and others, 2000). Agricultural runoff into lower Butte Creek results in an increase in nitrite plus nitrate concentrations. In contrast, the Colusa Basin Drain is primarily an agricultural drain (the entire drainage basin is within the Sacramento Valley) and nutrient concentrations are higher. Although the aggregated data for nitrate plus nitrite (fig. 21) suggest that nitrogen is not a problem in the Sacramento River Basin, algal population and chlorophyll data were not available and, therefore, the interpretation of nutrients such as nitrogen, phosphorus, and potassium is tentative. It is possible that the stimulation of algal growth by nutrients is causing a water-quality-control

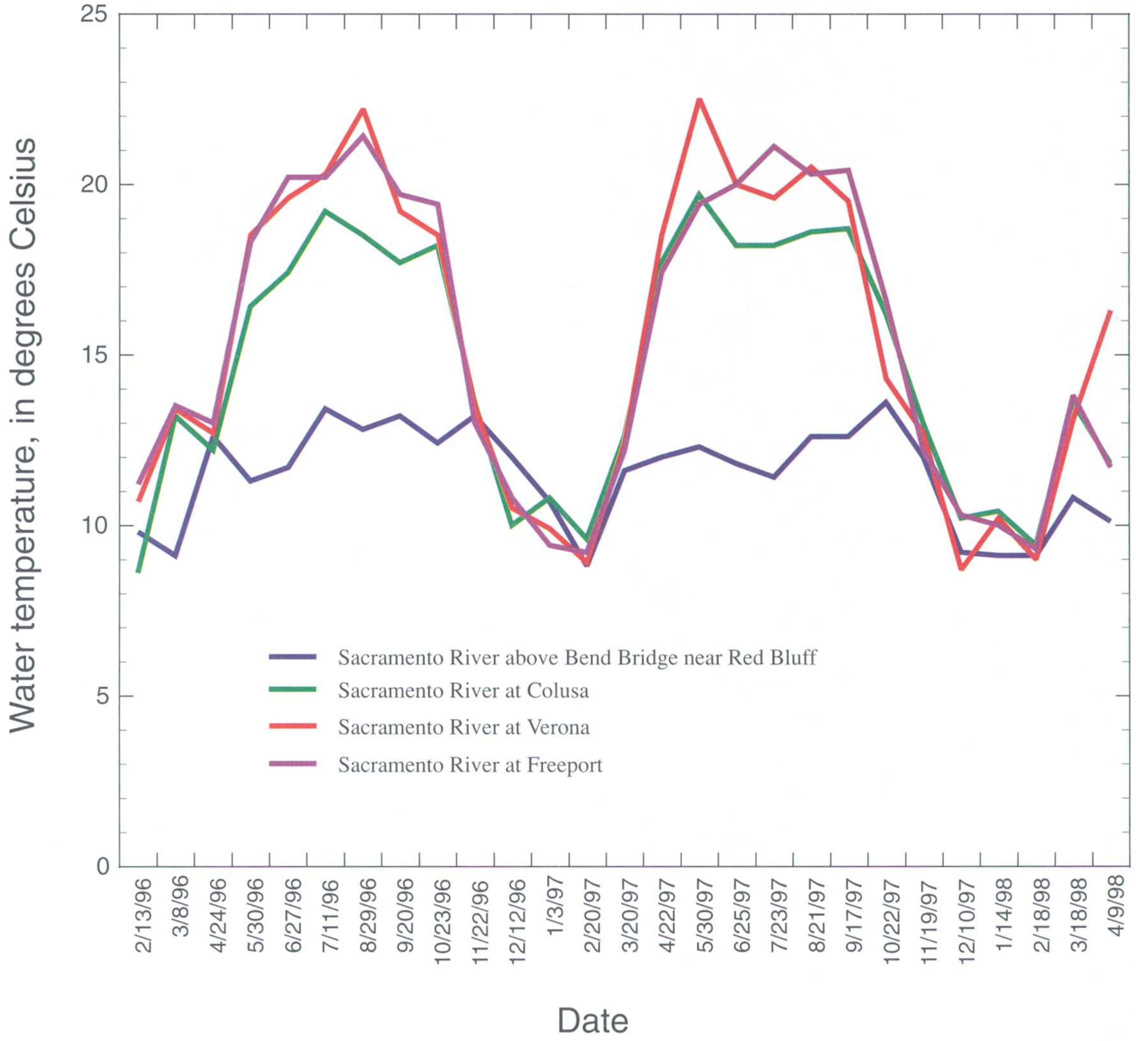


Figure 19. Time series plots of water temperature at four Sacramento River sites, California.

problem, but until additional information is available, further interpretations of nutrient concentrations are not possible.

Dissolved organic carbon is an important water-quality constituent for the Sacramento River because it is major source of drinking water in California. Chlorinating water (for disinfection purposes) that contains dissolved organic carbon can result in the formation of halogenated methane compounds—trichloromethane, bromodichloromethane, chlorodibromomethane, and tribromomethane (Thurman, 1985). Median dissolved organic carbon concentrations along the Sacramento River and its major eastern tributaries are similar, about 1.5 mg/L as carbon (fig. 22). When chlorinated, this level of dissolved organic carbon will not produce halogenated methane compounds exceeding drinking-water standards. Dissolved organic carbon concentrations in excess of 3 mg/L are more likely to produce

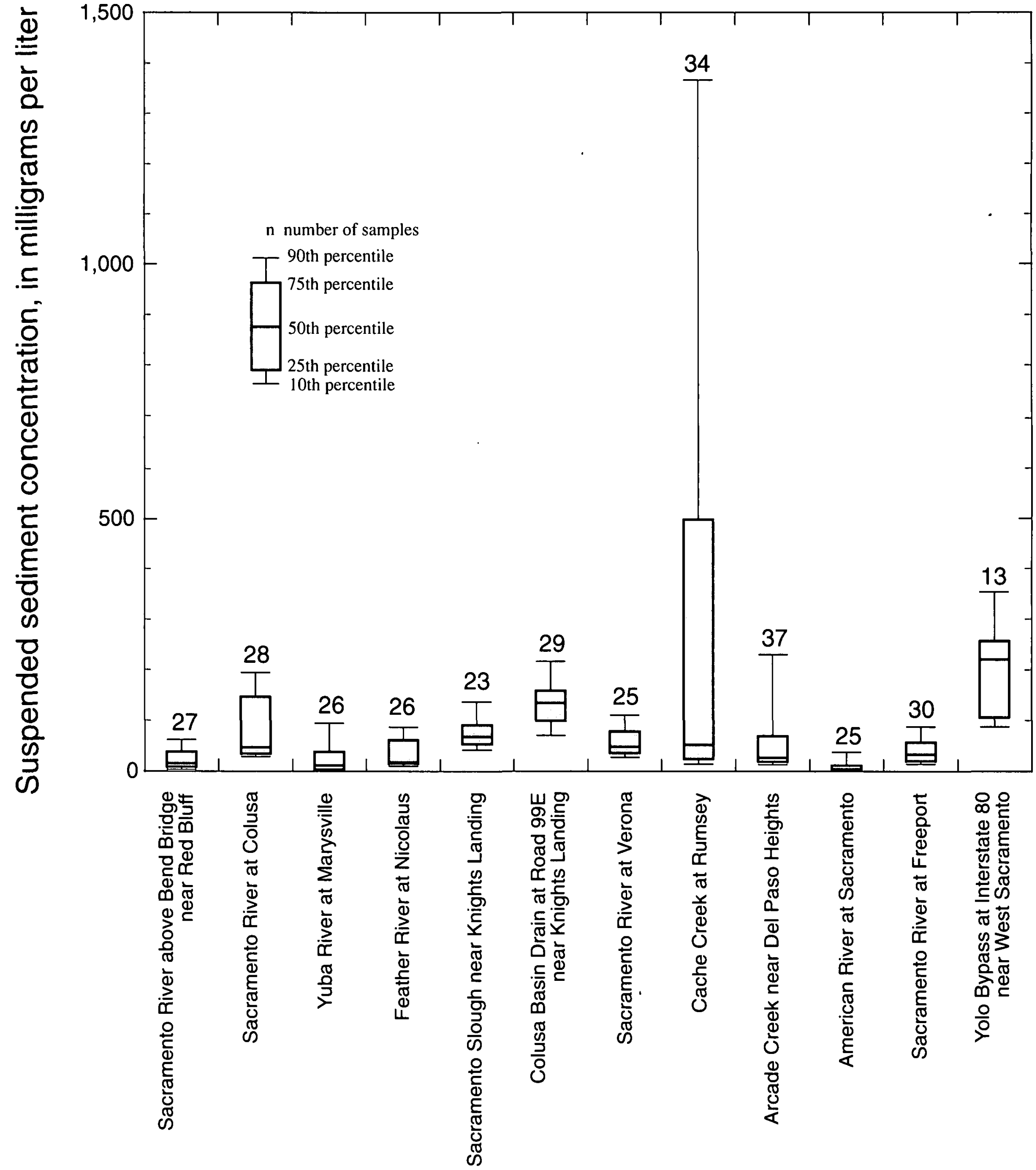


Figure 20. Boxplots of suspended sediment concentrations for the sampling sites in the Sacramento River Basin, California.

trihalomethane concentrations approaching or exceeding drinking-water standards (Lykins and Clark, 1989). Although the dissolved organic carbon concentrations of the Sacramento River are low, downstream tributaries within the Sacramento–San Joaquin River Delta also contribute dissolved organic carbon to the water of the California Aqueduct.

The lowest measured dissolved organic carbon concentrations were at the Yuba River at Marysville site; concentrations were higher at the two agricultural sites—the Sacramento Slough near Knights Landing and the Colusa Basin Drain at Road 99E near Knights Landing. Apparently, the agricultural land use of these basins, primarily rice farming, increases levels of dissolved organic carbon. The highest measured concentrations of dissolved organic carbon were at the Arcade Creek near Del Paso Heights site, indicating that urban runoff also is a source of dissolved organic

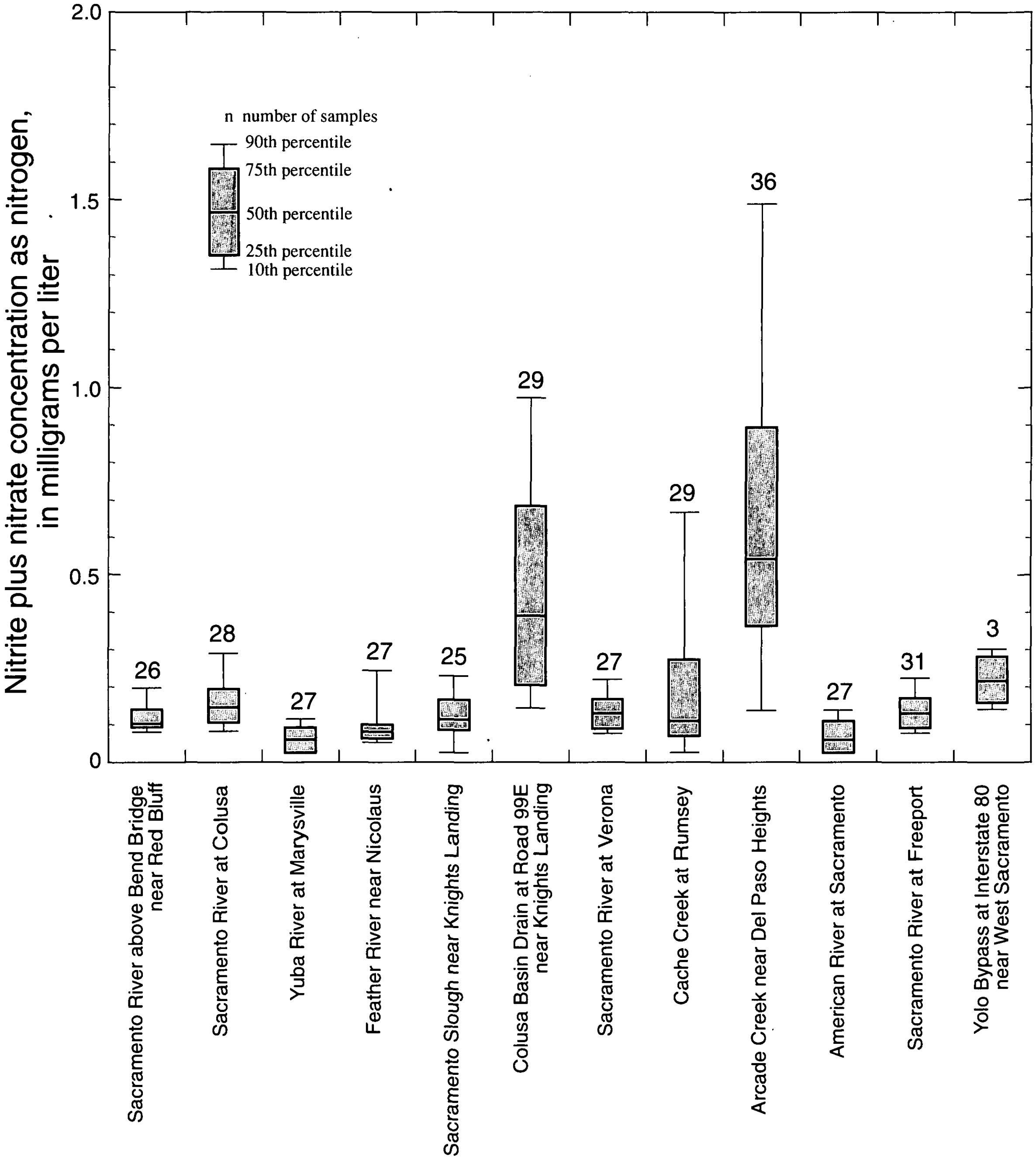


Figure 21. Boxplots of nitrite plus nitrate concentrations for the sampling sites in the Sacramento River Basin, California.

carbon. Dissolved organic carbon concentrations of the Cache Creek at Rumsey site tend to be higher than those of the Sacramento River sites, but less than those of the agricultural sites. Because Cache Creek water is derived primarily from Clear Lake, which has a known nutrient problem (U.S. Environmental Protection Agency, accessed October 1, 1999), it is not surprising to find relatively high levels of dissolved organic carbon at the Cache Creek at Rumsey site.

Major-Ion Chemistry

A trilinear diagram of fixed-site water chemistry for the summer is shown on figure 23. The water composition of the Sacramento River sites is similar at all four locations as indicated by the trilinear plot (fig. 23). There are slight differences in the cation composition of the three eastern tributary sites—the Yuba River at Marysville, the Feather River near Nicolaus, and the American River at Sacramento. The

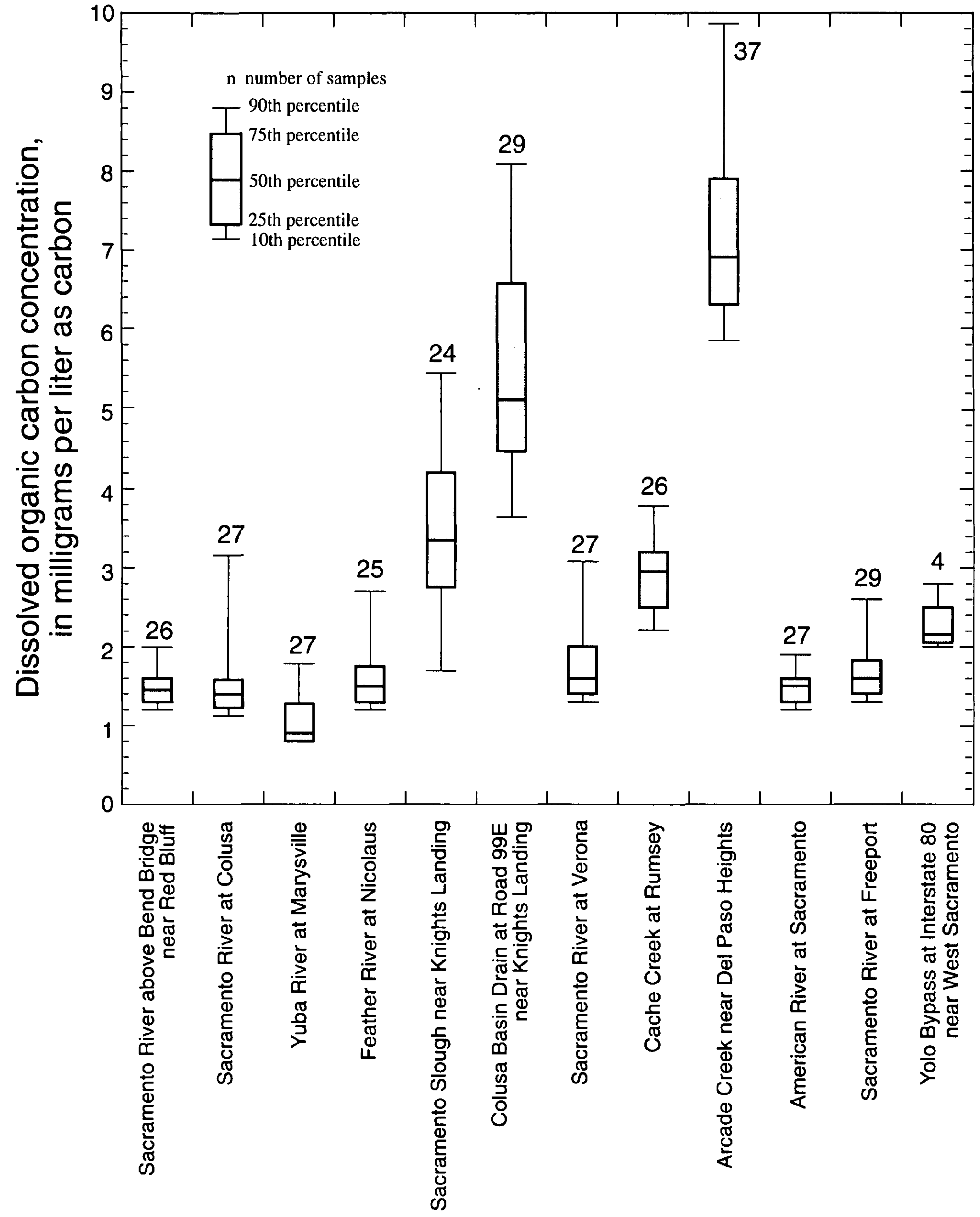


Figure 22. Boxplots of dissolved organic carbon concentrations for the sampling sites in the Sacramento River Basin, California.

Yuba River has a greater percentage of calcium, whereas the American River has a greater percentage of magnesium. The Feather River is very slightly enriched in sodium plus potassium. The Colusa Basin Drain at Road 99E near Knights Landing has the greatest difference in cation chemistry in relation to the other sites and has the highest percentage of sodium plus potassium. Most sites have similar anion chemistry, with bicarbonate as the dominant ion at all sites. The Colusa Basin Drain at Road 99E near Knights Landing is slightly enriched in chloride and sulfate in relation to the other sites, and the Arcade Creek near Del Paso Heights is enriched in chloride.

Water composition for the winter high-flow season is shown in the trilinear diagram on figure 24. Dilution from higher flows during the winter results in some changes in water composition. The cation compositions of the Sacramento River sites and large eastern tributary sites become more similar; the anion compositions of the Colusa Basin Drain at Road 99E near Knights Landing site and of the Arcade Creek near Del Paso Heights site plot closer to the bicarbonate composition typical of the other sites. Seasonal changes in cation and anion chemistry are apparent for the Cache Creek at Rumsey site (fig. 25). During November and December in 2 successive years, the composition of the water changed such that a greater percentage of cations was sodium plus potassium and a greater percentage of anions was chloride. Streamflow in Cache Creek tends to be very low during these 2 months because the flow from Clear Lake and Indian Valley Reservoir is reduced in response to a lower need for irrigation water. Bear Creek, a tributary of Cache Creek, has a naturally high salinity because of inflow from Wilbur Hot Springs (Hull, 1984). The higher sodium and chloride concentrations in Cache Creek during late autumn can be attributed to the higher salinity from Bear Creek. Slight variations in water composition also are apparent for the Arcade Creek near Del Paso Heights site (fig. 26). These changes probably can be attributed to differences in source water used to irrigate lawns and gardens (for example, ground water provided by utilities).

Trace Metals

Samples of trace metals in filtered water were collected to compare measured concentrations with water-quality standards. The trace metals discussed in this section are those which are known to have caused water quality impairments to various rivers and streams of the Sacramento River Basin, or are discussed for scientific reasons. Metals with consistently low or nondetectable concentrations are not discussed. Concentrations of all metals sampled are available from Domagalski and others (2000). Boxplots of selected metals for the period of study are shown on figure 27. Observed metal concentrations are attributable to natural or geological sources, and to anthropogenic factors such as mining, agricultural, or urban runoff.

Arsenic is not a true metal but is classified chemically as a metalloid. The current drinking-water standard (maximum contaminant level) for arsenic is 50 μg/L (Marshack, 1995). However, that standard may be lowered to 5 μg/L (U.S. Environmental Protection Agency, 2000). Boxplots of arsenic concentration are shown on figure 27*A*. The concentrations of arsenic in filtered water are below the current drinking-water standard of 50 μg/L. At most sites, the median concentrations are near 1 μg/L, which was the detection limit for the arsenic analyses of this study. The higher concentrations of arsenic at the agricultural indicator sites appear to have a minimal effect on the arsenic concentrations measured at the Sacramento River at Verona site. This can be attributed to dilution by the higher flows in the Sacramento River in relation to the flows of the agricultural indicator streams.

Chromium is enriched in the marine rocks of the Coast Ranges physiographic province in relation to the mixed rock types of the Sierra Nevada and Middle Cascade mountains. As a result, the chromium concentrations were highest at the Colusa Basin Drain at Road 99E near Knights Landing and the Cache Creek at Rumsey sites (fig. 27*B*). The source or sources of chromium to the Sacramento Slough are unknown. All chromium concentrations were less than the drinking-water standard, 100 μg/L for total chromium (U.S. Environmental Protection Agency, 2000).

Copper was mined at numerous locations in the Klamath Mountains west of Shasta Lake (fig. 4). The median concentration of copper in filtered water from the Sacramento River at the site above Bend Bridge near Red Bluff and the site at Colusa was about 1.5 μg/L (fig. 27*C*). It was not determined whether those concentrations are due to historical upstream mining operations or natural background levels. Slightly elevated copper concentrations were measured at the Sacramento Slough near Knights Landing and Colusa Basin Drain at Road 99E near

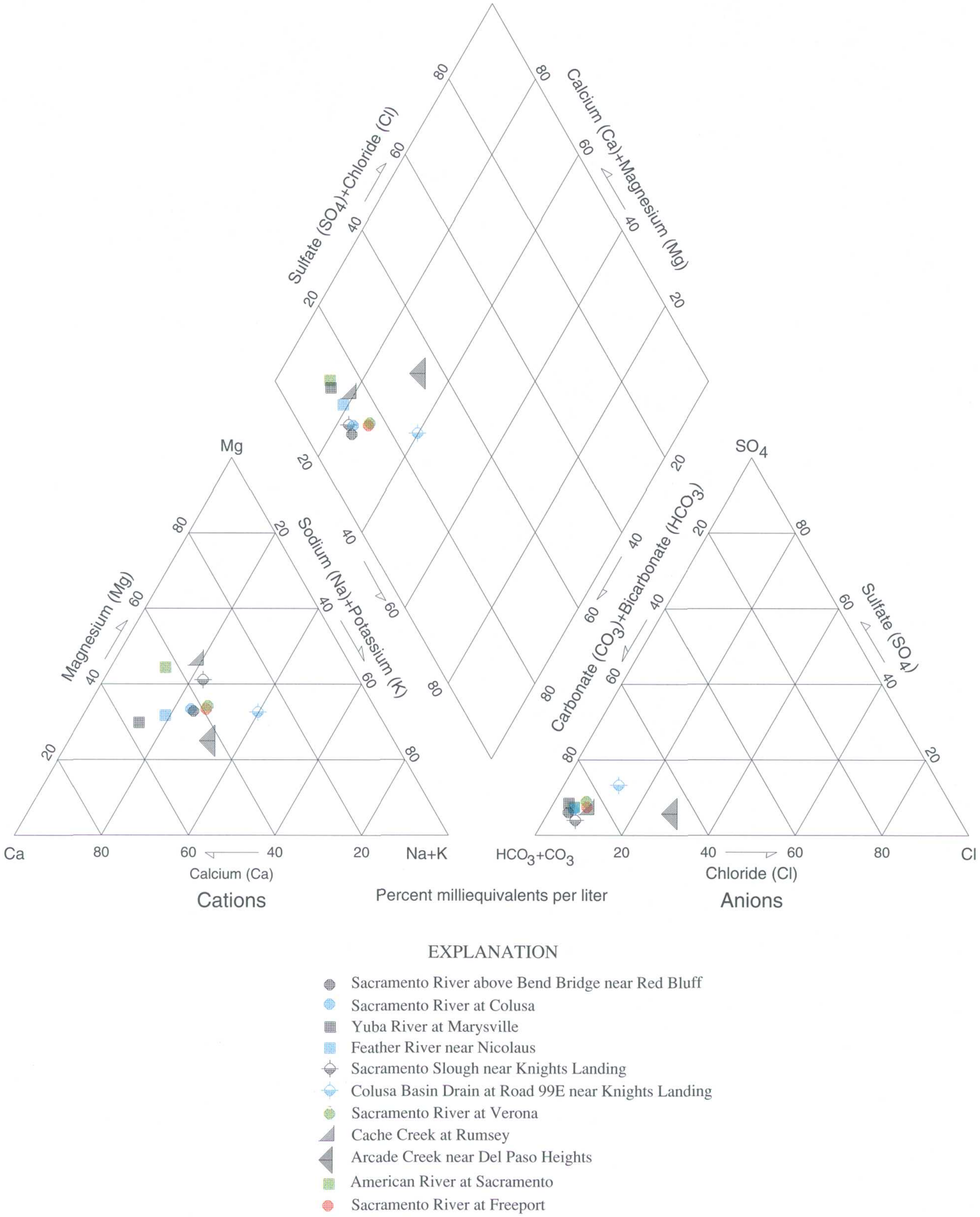


Figure 23. Trilinear diagram of major ion composition in water samples collected during the summer from the basic fixed sites in the Sacramento River Basin, California.

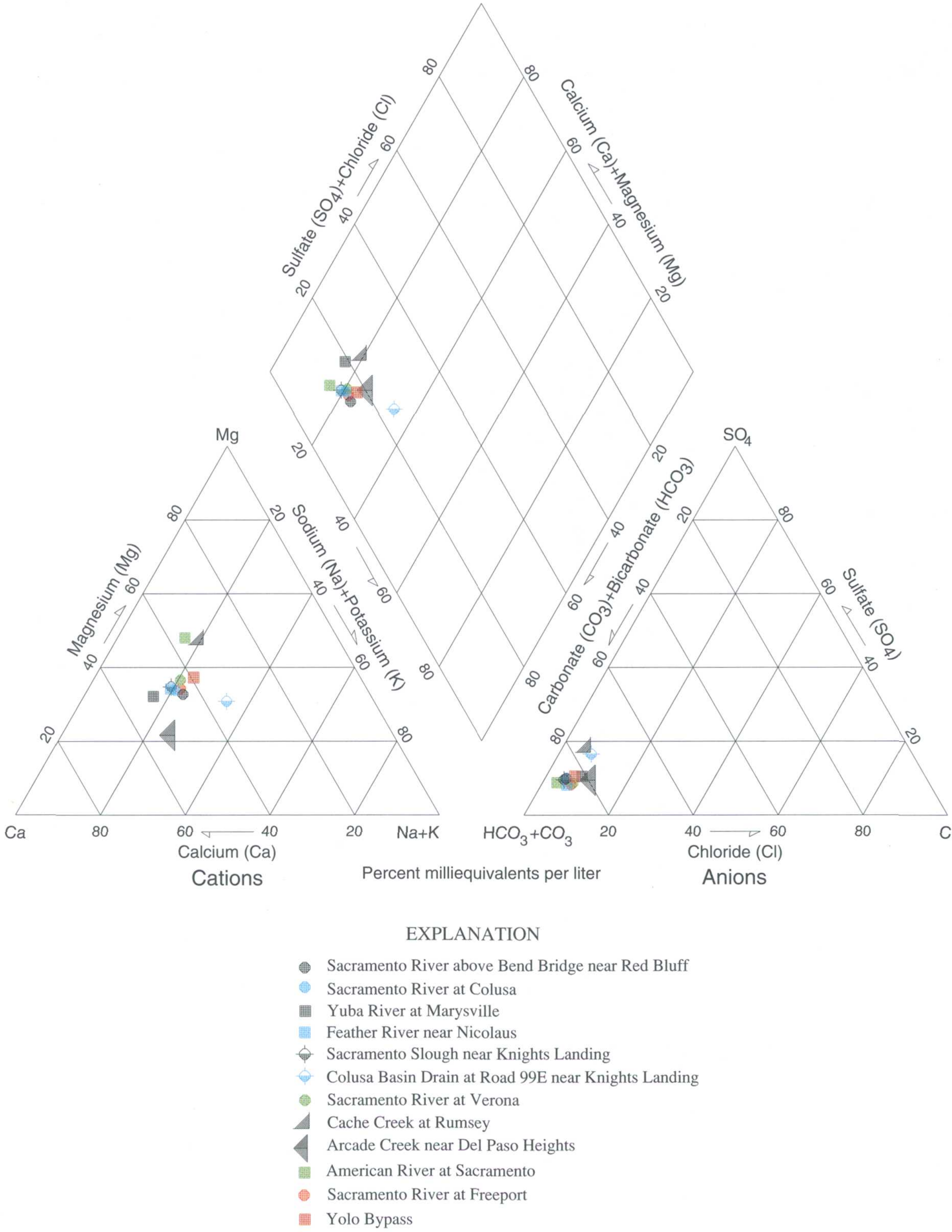


Figure 24. Trilinear diagram of major ion composition in water samples collected during the winter from the basic fixed sites in the Sacramento River Basin, California.

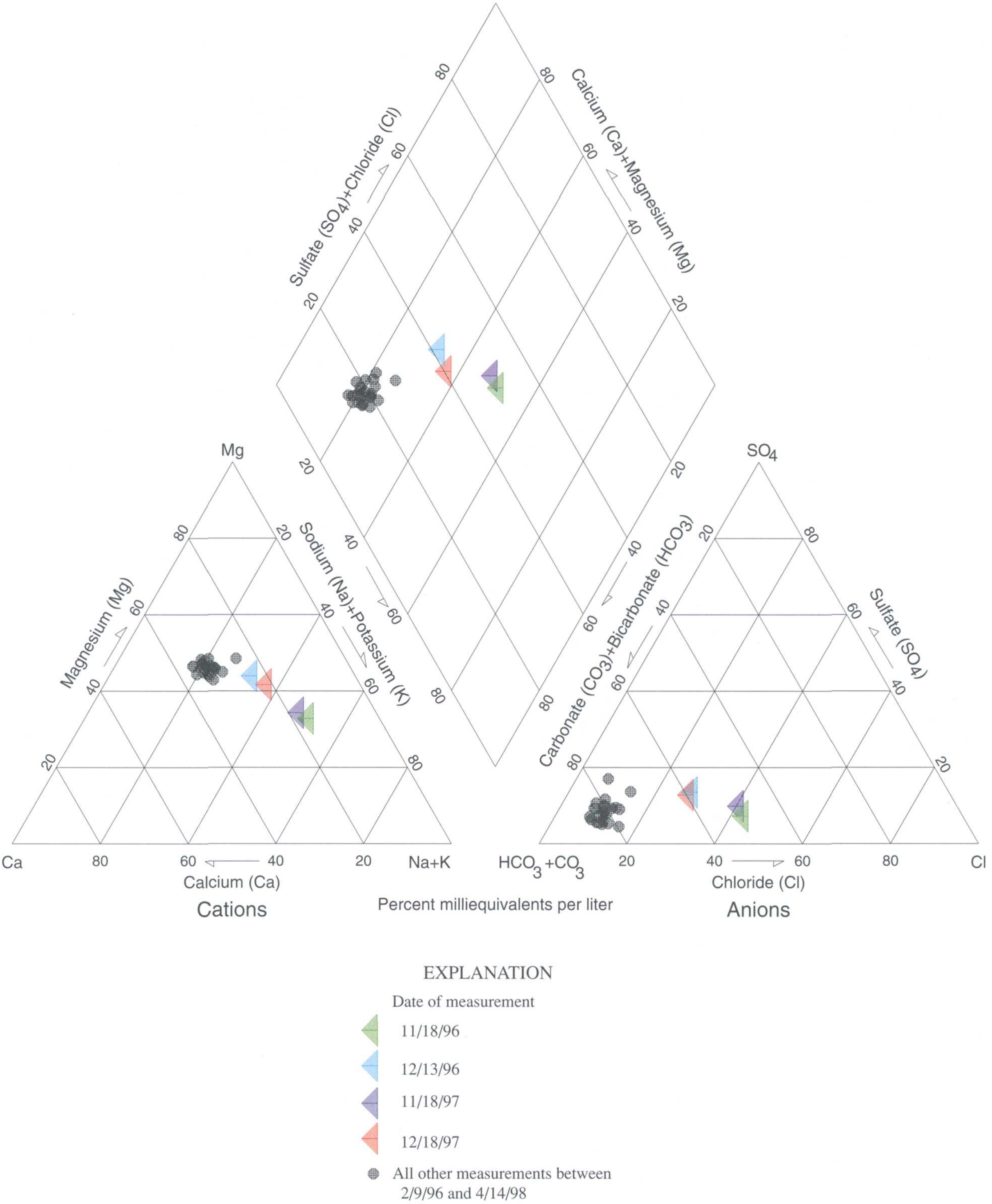
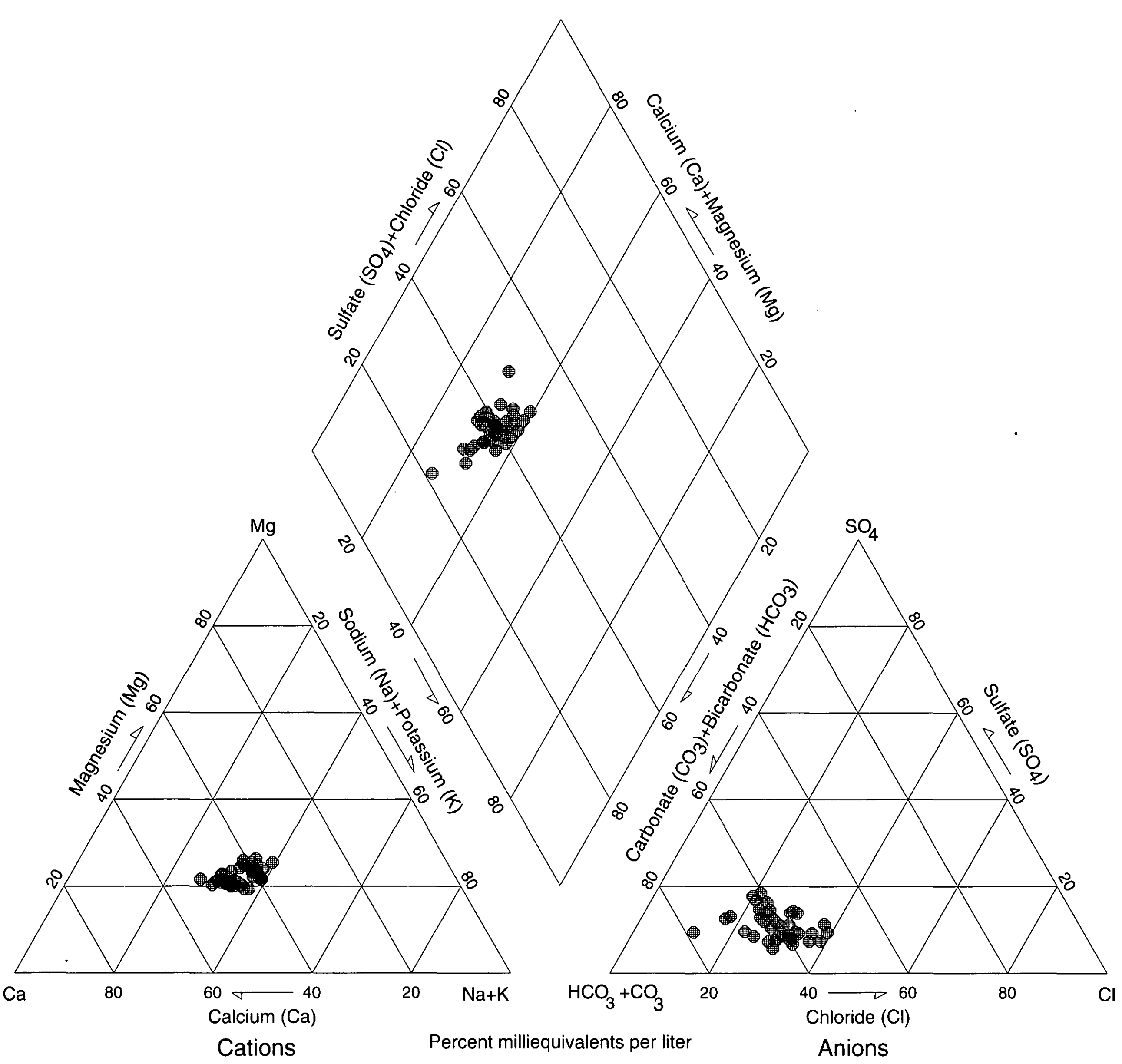


Figure 25. Trilinear diagram of major ion composition in water samples from the Cache Creek at Rumsey site, Sacramento River Basin, California.



EXPLANATION

● Samples collected between 2/6/96 and 4/23/98

Figure 26. Trilinear diagram of major ion composition in water samples from the Arcade Creek near Del Paso Heights sampling site, Sacramento River Basin, California.

Knights Landing sites (fig. 27*C*). Rice is a major crop of those two basins, and copper is generally added to flooded rice fields to control algae. The copper concentrations at these sites were highest shortly after the April through May application season. However, the highest measured copper concentrations occurred at the Arcade Creek near Del Paso Heights site and are attributed to urban runoff. Copper concentrations at all sites were well below the action level for copper in drinking water, 1,300 µg/L (U.S. Environmental Protection Agency, 2000).

Concentrations of nickel (fig. 27*D*) were higher at the agricultural sites and the urban site. All nickel

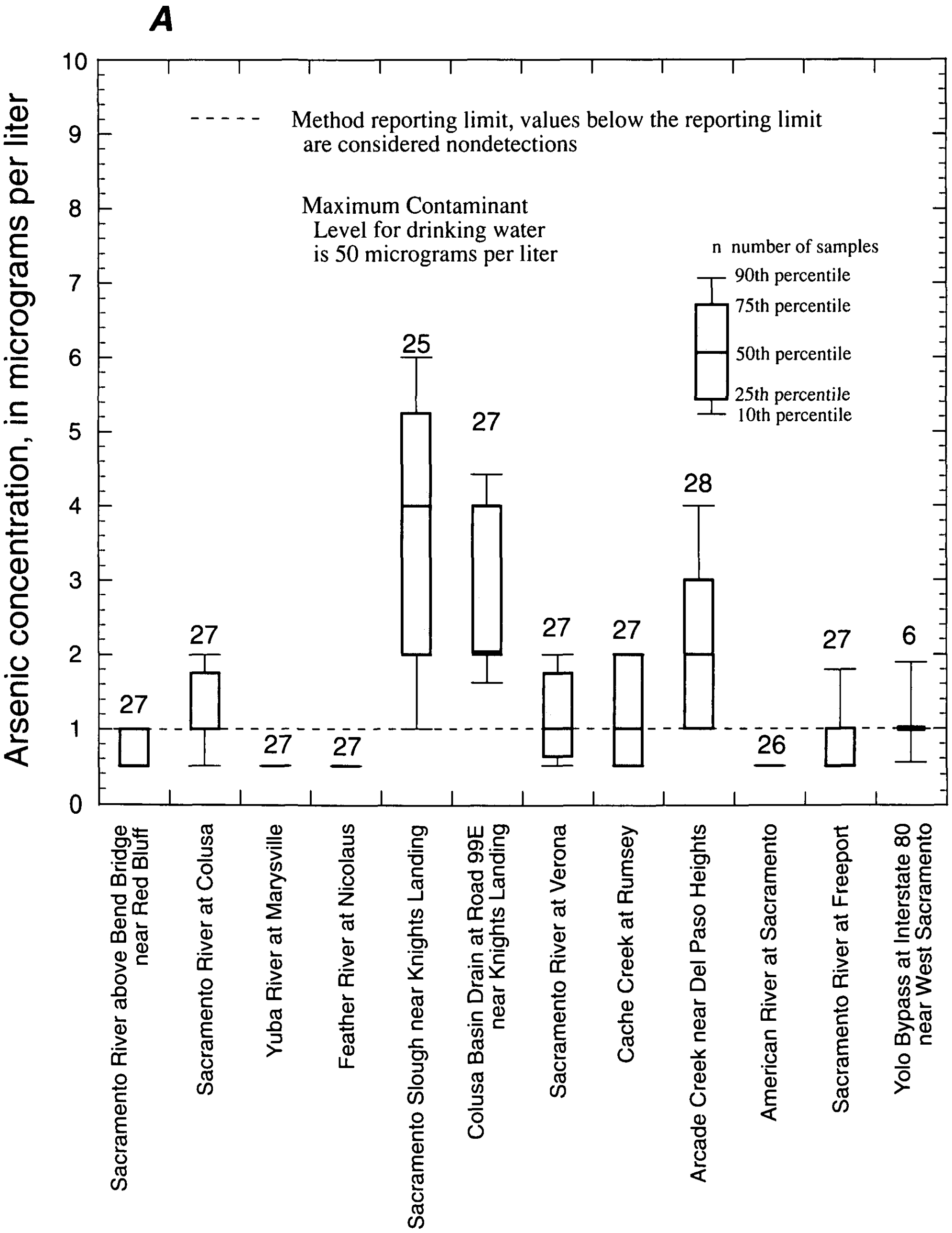


Figure 27. Boxplots of concentrations for the basic fixed sites in the Sacramento River Basin, California: (*A*) Arsenic. (*B*) Chromium. (*C*) Copper.(*D*) Nickel. (*E*) Zinc . On boxes with no visible 50th percentile mark, the 50th percentile falls on the 25th or 75th percentile as shown by the bolder line.

concentrations were less than the California drinking-water standard of 100 µg/L (Marshack, 1995).

Zinc concentrations (fig. 27*E*) were low throughout the Sacramento River Basin, except for the Arcade Creek near Del Paso Heights site. The higher concentrations at that site were attributed to urban runoff. Zinc concentrations were less than the (nonenforceable) drinking-water standard (secondary maximum contaminant level) of 5,000 µg/L (U.S. Environmental Protection Agency, 2000).

Concentrations of copper and zinc in the upper Sacramento River, below Keswick Dam, have been considered problematic in past years because of exceedances of water quality standards for protection of aquatic life and toxicity to fish (CH2M Hill, 1992). Water quality of the Sacramento River below Keswick

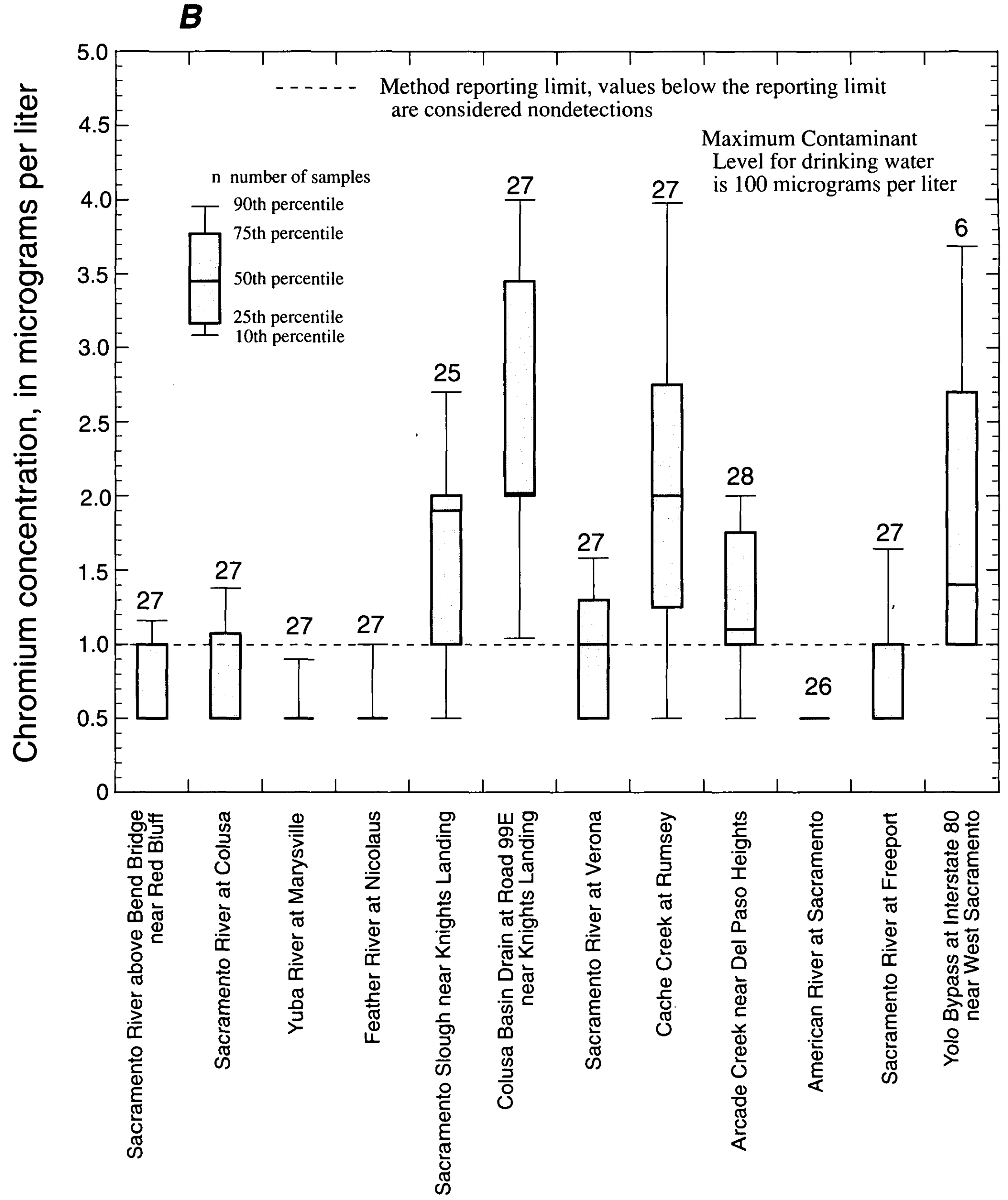


Figure 27.—*Continued.*

Dam can be managed by controlling the amount of discharge from Shasta Lake and Keswick Reservoir (CH2M Hill, 1992). The discharges are set to maintain the Sacramento River concentrations of copper, zinc, and other metals below water-quality standards. The aquatic-life standards for metals are written with respect to water hardness. Boxplots of water hardness for the fixed sites are shown on figure 28. The formula for the 4-day criterion of continuous average copper concentration in filtered water (Marshack, 1995) is

$$4\text{-}day\ copper\ average\ =$$

$$e^{\{0.8545[\ln(hardness)]-1.454\}} \times 0.960 \qquad (1)$$

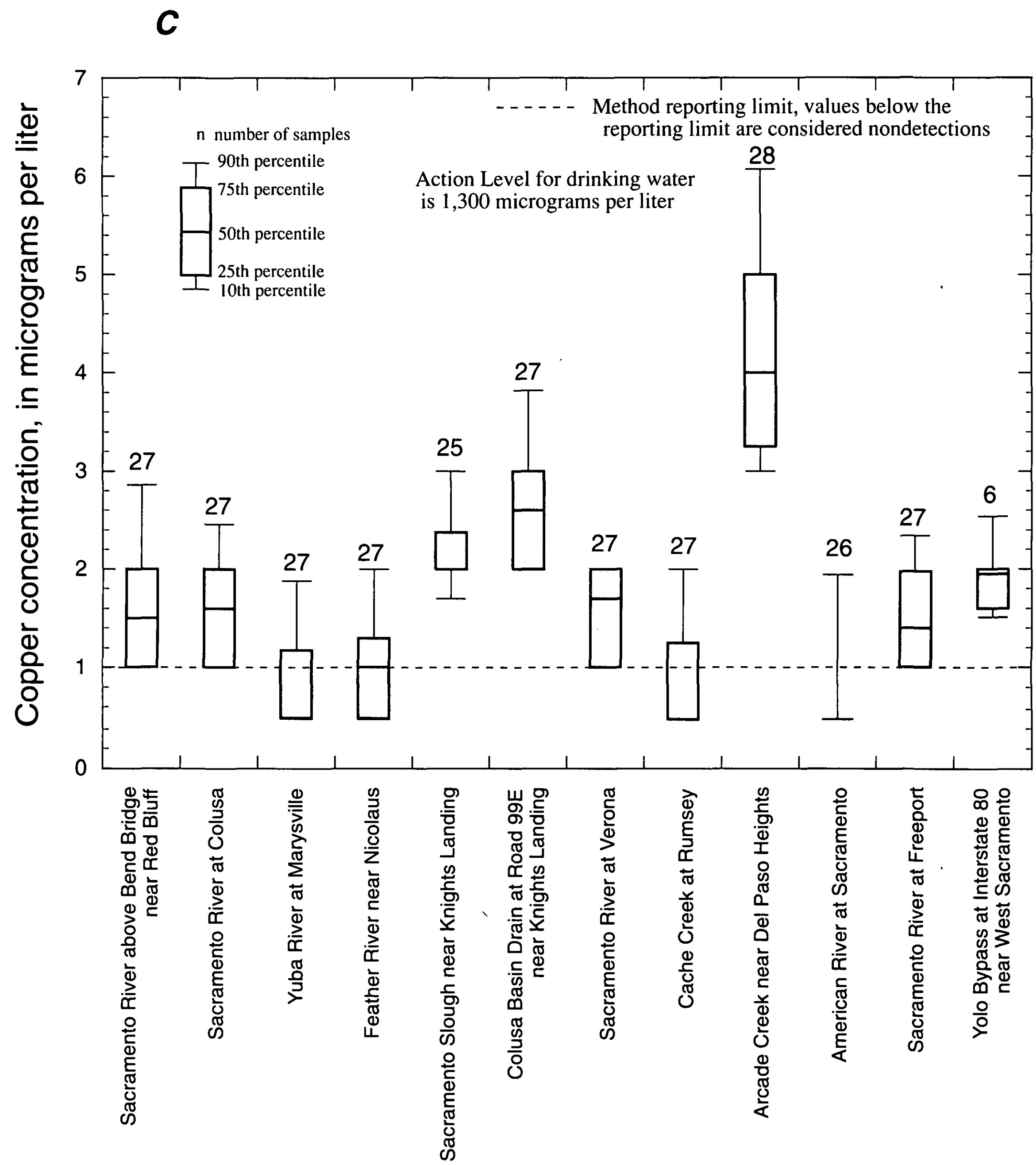


Figure 27.—*Continued.*

The median hardness for the Sacramento River above Bend Bridge near Red Bluff site is 49 mg/L as calcium carbonate. Therefore, the calculated median regulatory limit for copper for the protection of aquatic life at the Sacramento River above Bend Bridge near Red Bluff site is 6.2 µg/L in filtered water, using a 0.45-µm filter. Copper concentrations did not exceed the standard for that site or for any of the downstream sites on the Sacramento River during the timeframe of this study. Higher copper concentrations were measured at the Colusa Basin Drain at Road 99E near Knights Landing and the Arcade Creek near Del Paso Heights sites; the highest measured concentrations were 6 and 7 µg/L, respectively. Neither of those concentrations exceed the copper standard when adjusted for hardness.

The aquatic-life standard for zinc is also dependent on water hardness. The formula for the

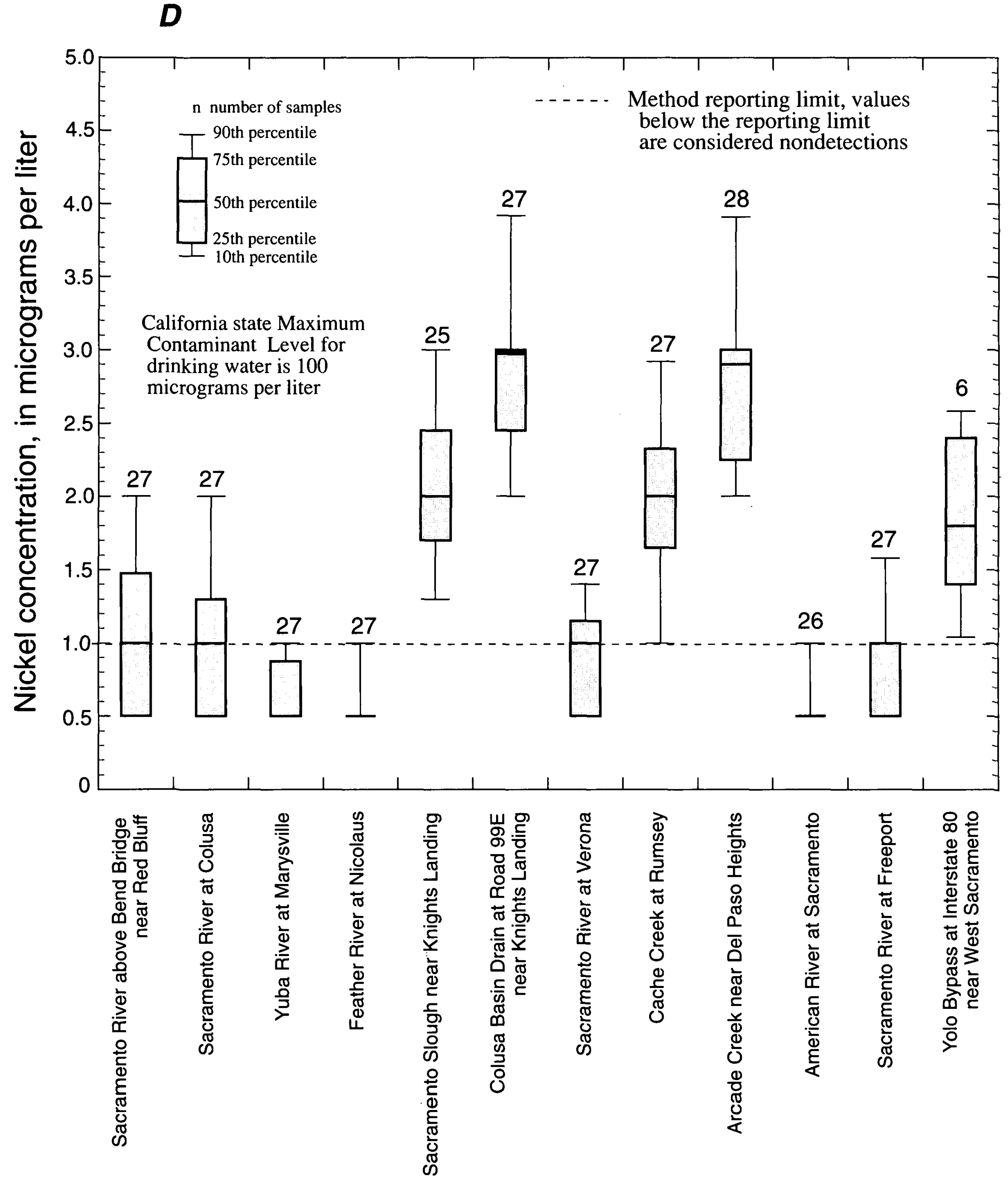


Figure 27.—*Continued.*

4-day criterion of continuous average zinc concentration in filtered water (Marshack, 1995) is

$$4\text{-}day\ zinc\ average = e^{\{0.8473[\ln(hardness)]\ + 0.7614\}} \times 0.986 \qquad (2)$$

For a median hardness of the Sacramento River above Bend Bridge near Red Bluff of 49 mg/L as calcium carbonate, the calculated median regulatory limit for zinc for the protection of aquatic life is 57 µg/L in filtered water, using a 0.45-µm filter. None of the sites on the Sacramento River or the tributaries, including any of the agricultural indicator sites or the urban

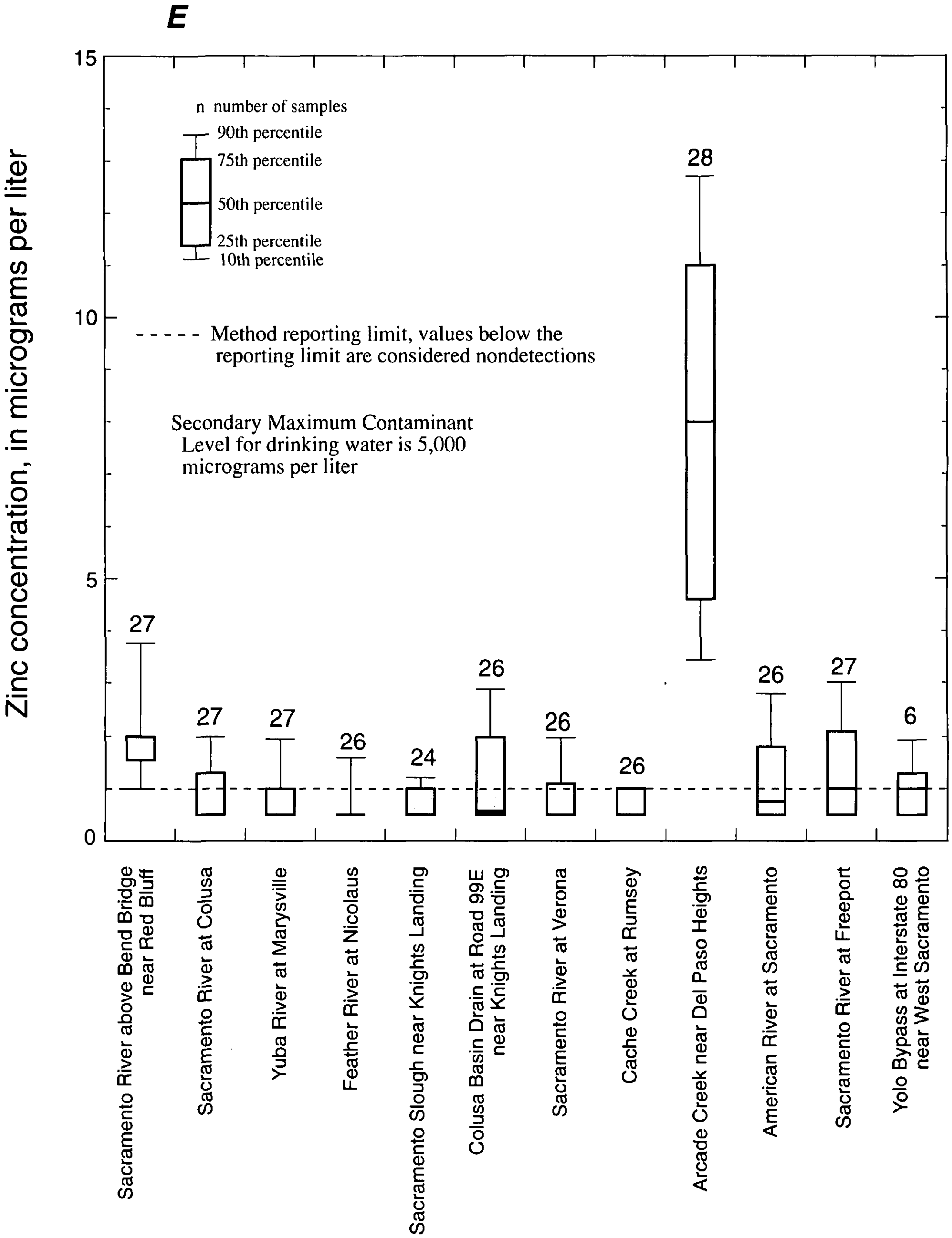


Figure 27.—*Continued.*

indicator site, had any exceedances of the zinc standard for the period of this study.

Mercury and Methylmercury

Mercury and methylmercury concentrations were measured in unfiltered water samples. Most mercury is attached to particles of suspended sediment (Horowitz, 1995), and current water-quality standards for mercury, with respect to the protection of aquatic health, are written for concentrations in unfiltered water (Marshack, 1995). Mercury was measured at all fixed sites, but methylmercury was measured at only five sites. Methylmercury sampling was designed to

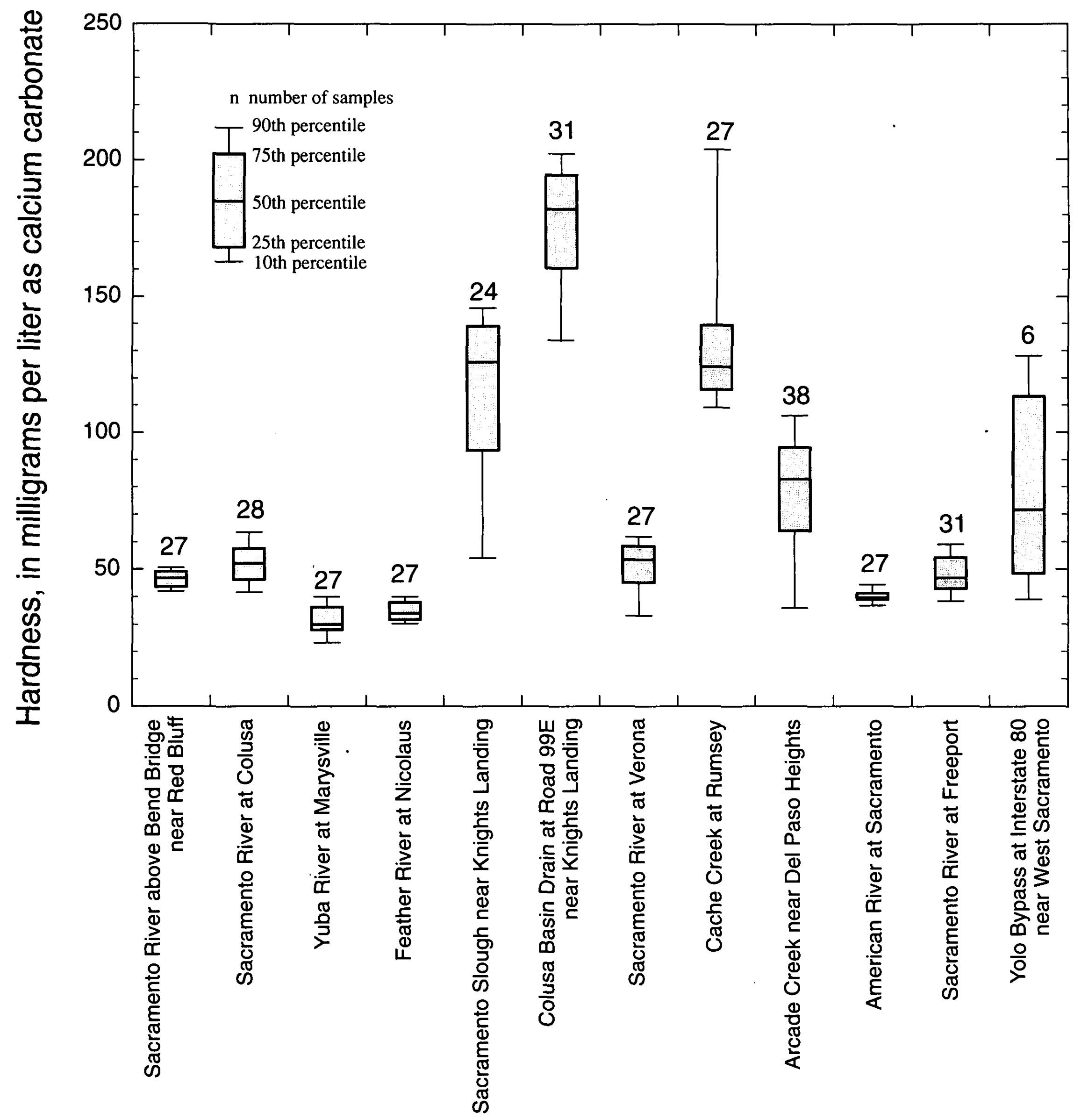


Figure 28. Boxplots of water hardness for the basic fixed sites in the Sacramento River Basin, California.

test the hypothesis that rice cultivation affects the concentrations of methylmercury in water. Wetland environments are ideal for the formation of methylmercury (Zilloux and others, 1993). Artificial wetlands are created during the rice growing season when each rice field is continually flooded with water. The two agricultural sites—the Colusa Basin Drain at Road 99E near Knights Landing and the Sacramento Slough near Knights Landing—were chosen for methylmercury sampling. The Sacramento River at Colusa, which is upstream from most of the rice field drainage, was chosen as a control site. It is assumed that methylmercury concentrations measured at the Sacramento River at Colusa are not the result of rice cultivation. The Sacramento River at Verona site, which is just downstream from where most of the rice field drainage enters the Sacramento River, also was chosen for methylmercury sampling. Finally, the Sacramento River at Freeport was chosen for methylmercury sampling to determine the concentrations at the most downstream site on the Sacramento River.

Boxplots of mercury concentrations in unfiltered water are shown on figure 29. The two sites with the highest concentrations are the Cache Creek at Rumsey and the Yolo Bypass at Interstate 80 near West Sacramento. It was expected that the highest

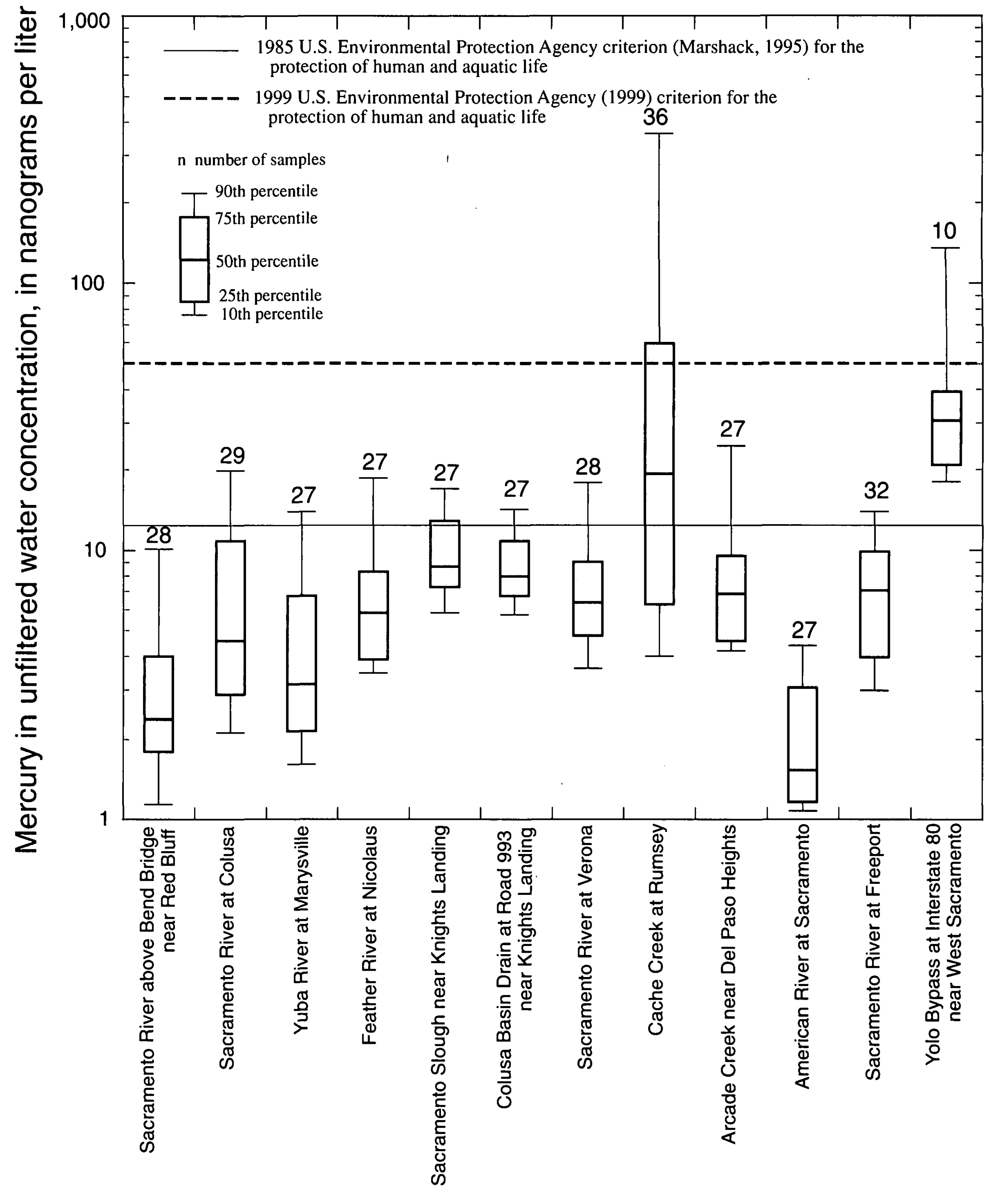


Figure 29. Boxplots of mercury in unfiltered water for the basic fixed sites in the Sacramento River Basin, California.

concentrations would be detected at these two sites because of the mercury mines in the Cache Creek Basin and Yolo Bypass carries stormwater runoff from the entire Sacramento River Basin, including the Cache Creek Basin. Mercury concentrations correlate well with suspended-sediment concentrations measured in Cache Creek at Rumsey; the highest concentrations were during the winter of 1997–1998 (fig. 30). Sediment and mercury concentrations aggregated for all 12 sites are shown on figure 31. A second order equation can be fitted to the data with a resulting coefficient of determination (r^2) of 0.96. Previous studies (for example, Mastrine and others, 1999) have shown a correlation between mercury in

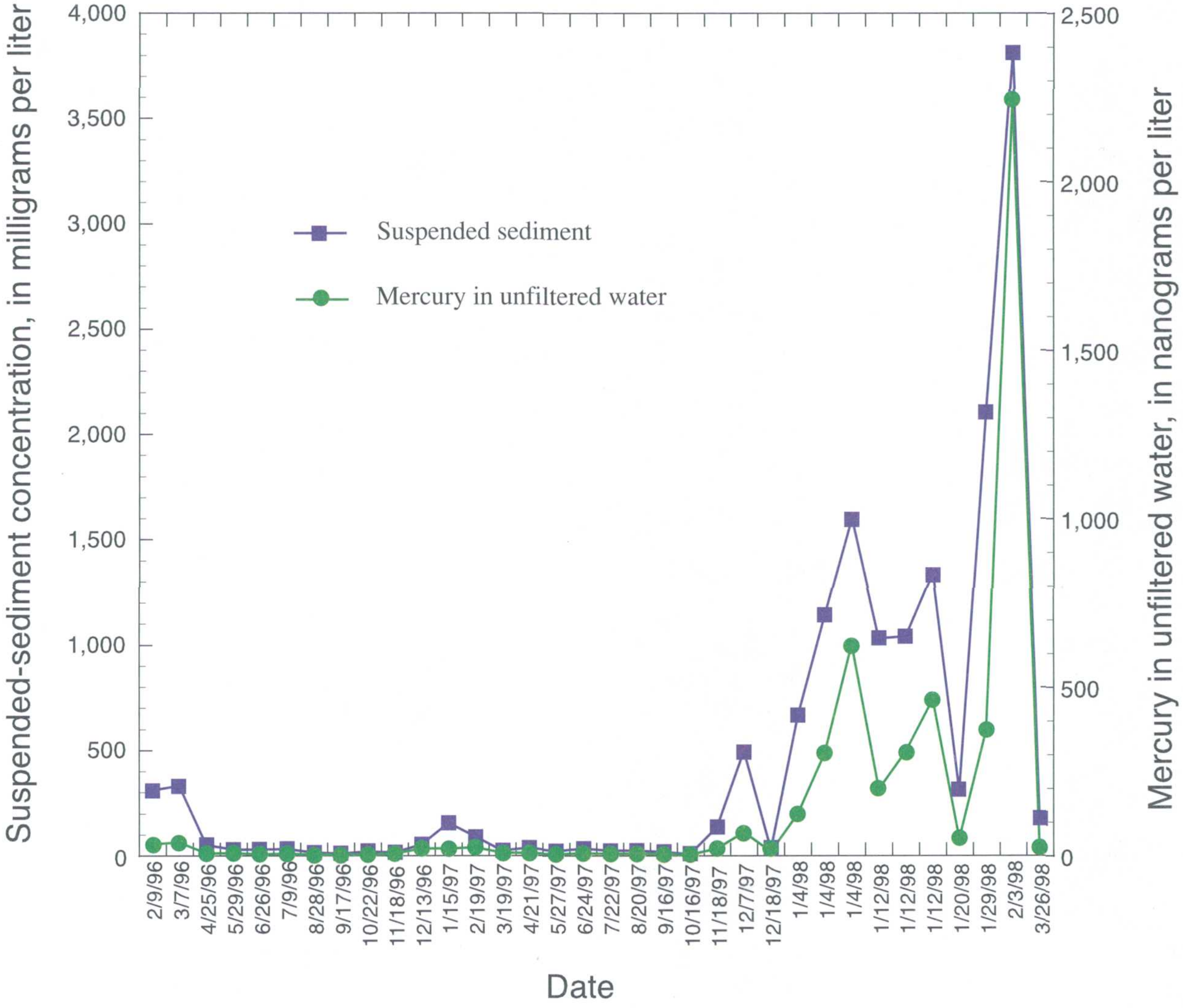


Figure 30. Time series plot of suspended sediment and mercury concentrations in unfiltered water for the Cache Creek at Rumsey site, Sacramento River Basin, California. Stormwater runoff samples were collected only in 1998.

unfiltered water and suspended sediment concentrations in precious metals mining areas. Mastrine and others (1999) noted a linear relationship between the two variables, but the mercury concentrations in that study (southeastern United States) were much lower than those reported here. Although the plot on figure 30 shows much higher concentrations of suspended sediment and mercury during the winter of 1997–1998, no storm-water samples were collected during the winter of 1996–1997. Had storm samples been collected during the winter of 1996–1997, it is likely that higher concentrations of suspended sediment and mercury would have been recorded. Stormwater runoff samples were collected at the Sacramento River sites during the winters of 1996–1997 and 1997–1998. A time-series plot of mercury and suspended-sediment concentrations for the Sacramento River at Colusa site shows the same pattern as Cache Creek; the higher mercury concentrations occur when suspended-sediment concentrations also are elevated. Suspended-sediment and mercury concentrations are lower in the late spring to autumn because there is little rainfall and suspended sediment transport.

The lowest measured concentrations of mercury in unfiltered water were from the Sacramento River above Bend Bridge near Red Bluff and the American River at Sacramento sites (fig. 29). However, it was expected that higher concentrations of mercury in unfiltered water would be from samples collected from

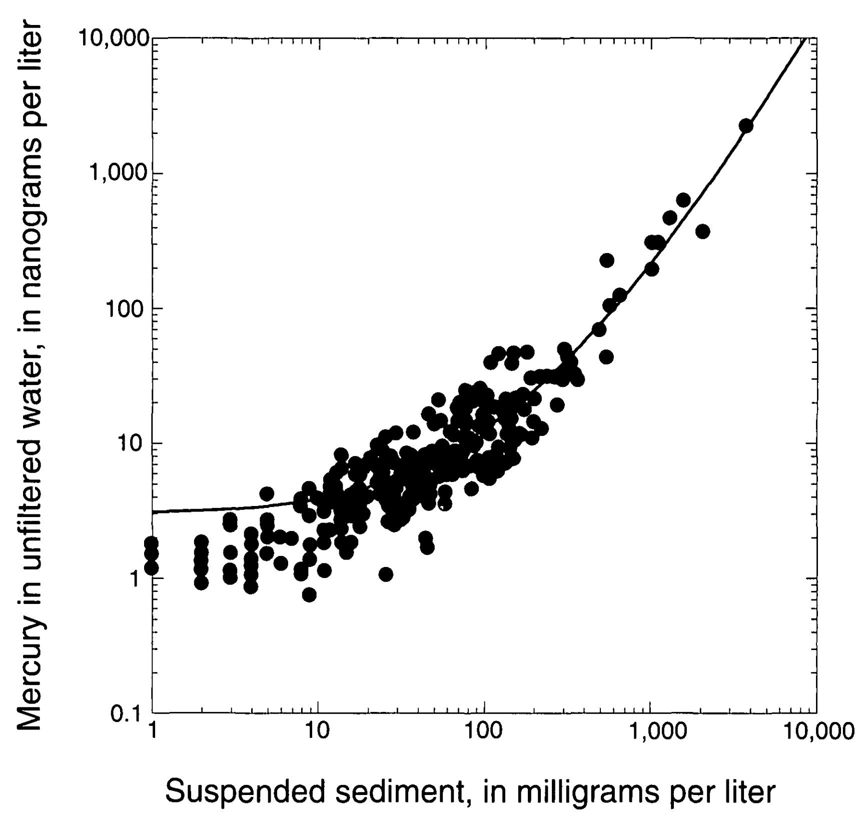


Figure 31. Plot of mercury in unfiltered water concentrations and total suspended sediment concentrations aggregated for all 12 sites, Sacramento River Basin, California.

the streams of the eastern part of the Sacramento River Basin associated with historical gold mining—the Feather River near Nicolaus, the Yuba River at Marysville, or the American River at Sacramento. Further, it was expected that those concentrations would significantly increase the loading at downstream sites. The median concentration of mercury in unfiltered water for the Feather River near Nicolaus site (5.8 ng/L) is higher than that of the Sacramento River above Bend Bridge near Red Bluff site (2.4 ng/L), and that difference is statistically significant (Mann–Whitney nonparametric test of medians, $p = 0.0002$). Although the median concentration of mercury in unfiltered water of the Feather River near Nicolaus (5.8 ng/L) is statistically similar to that of the Sacramento River at Colusa (4.5 ng/L) ($p = 0.4360$), higher concentrations were measured at the Sacramento River at Colusa site (fig. 29) even though it is above the confluence of the Sacramento and Feather rivers. During stormflow in January 1997, loadings of mercury in unfiltered water were higher at the Sacramento River at Colusa site than at the Feather River near Nicolaus site despite higher rainfall in the Feather River Basin (Domagalski, 1998); it was concluded that an unknown source of mercury must be present between Red Bluff and Colusa. That source may be anthropogenic or geologic (possibly both); features such as hot springs are associated with volcanic deposits in that region.

Stormwater runoff and associated high river flows affect the concentration of mercury in unfiltered water owing to higher suspended-sediment concentrations. Concentrations of mercury can exceed recommended criteria for protection of aquatic or human health during high-river flows. In 1985, the U.S. Environmental Protection Agency set a recommended criterion of 12 ng/L of total mercury in freshwater for the protection of aquatic and human health (Marshack, 1995). During the winter of 1996–1997, the 1985 criterion for mercury was exceeded at the Sacramento River at Colusa for 2 months, and at the Sacramento River at Freeport for 3 months. During the winter of 1997–1998, the criterion was exceeded at the Sacramento River at Colusa for 5 months and at the Sacramento River at Freeport for 3 months. More exceedances of the 12 ng/L criterion occurred at the Sacramento River at Colusa during the winter of 1997–1998 because of a longer-than-normal period of

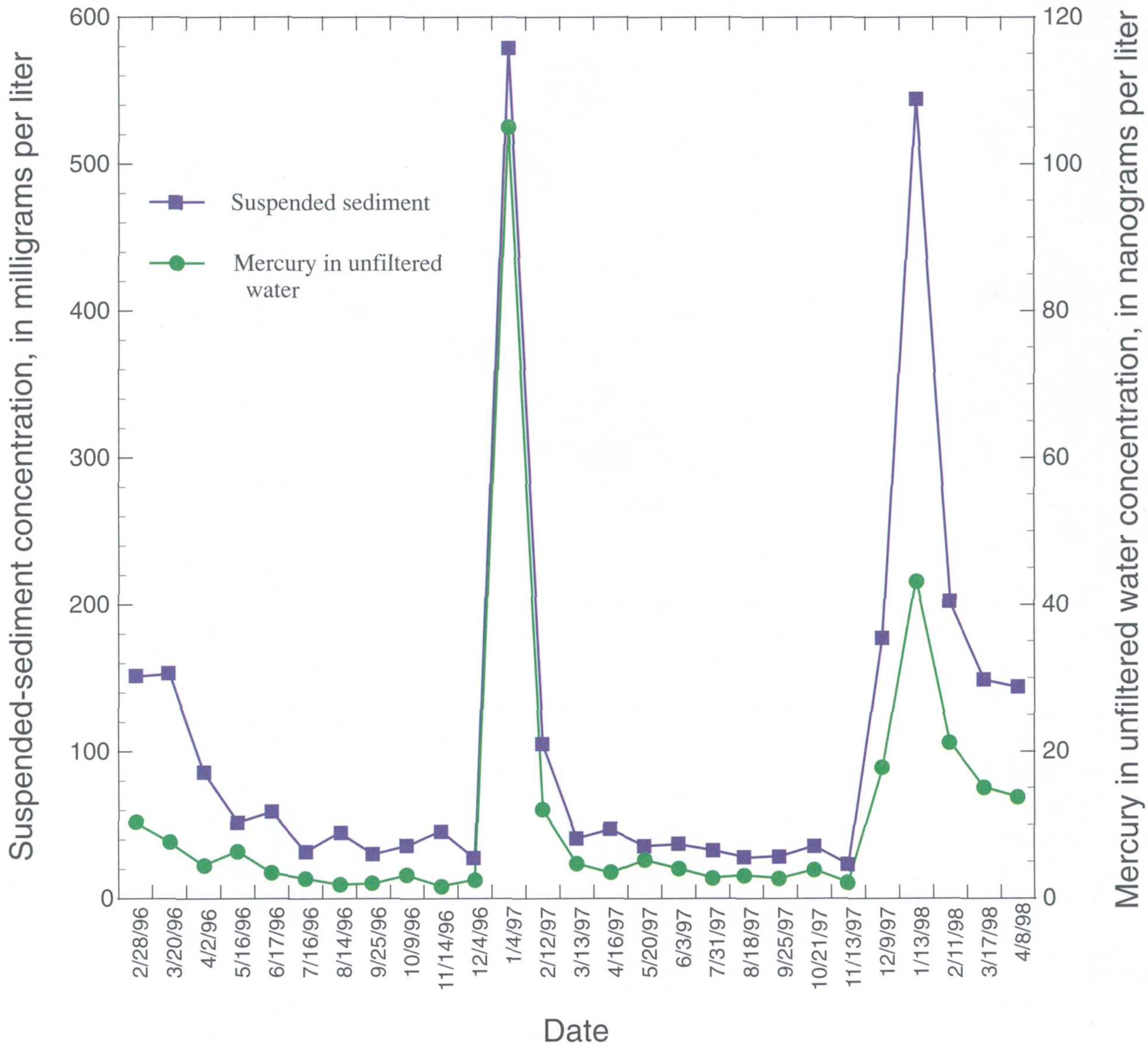


Figure 32. Time series plot of suspended sediment and mercury in unfiltered water concentrations for the Sacramento River at Colusa site, California.

rain. As mentioned previously, the winter of 1997–1998 was an El Niño winter. In 1999, the U.S. Environmental Protection Agency revised that recommended criterion to 50 ng/L (U.S. Environmental Protection Agency, 1999). In contrast, the 1999 criterion was not exceeded as frequently. Only the Cache Creek at Rumsey and the Yolo Bypass at Interstate 80 near West Sacramento sites had frequent exceedances.

Boxplots of methylmercury in unfiltered water for the five sites at which it was measured in this study are shown on figure 33. The highest median concentration of methylmercury (0.191 ng/L) was for the Colusa Basin Drain at Road 99E near Knights Landing site. As expected, the Sacramento River at Colusa site had the lowest median methylmercury concentration (0.102 ng/L). However, the data for the Sacramento River at Colusa have high variability, especially above the 50th percentile. Although no California or federal water quality standard for methylmercury has been established, a concentration at or below 0.1 ng/L has been suggested as being representative of pristine water (Rudd, 1995). Those concentrations are typical of rivers upstream from wetland environments and away from mercury sources. The median methylmercury concentrations

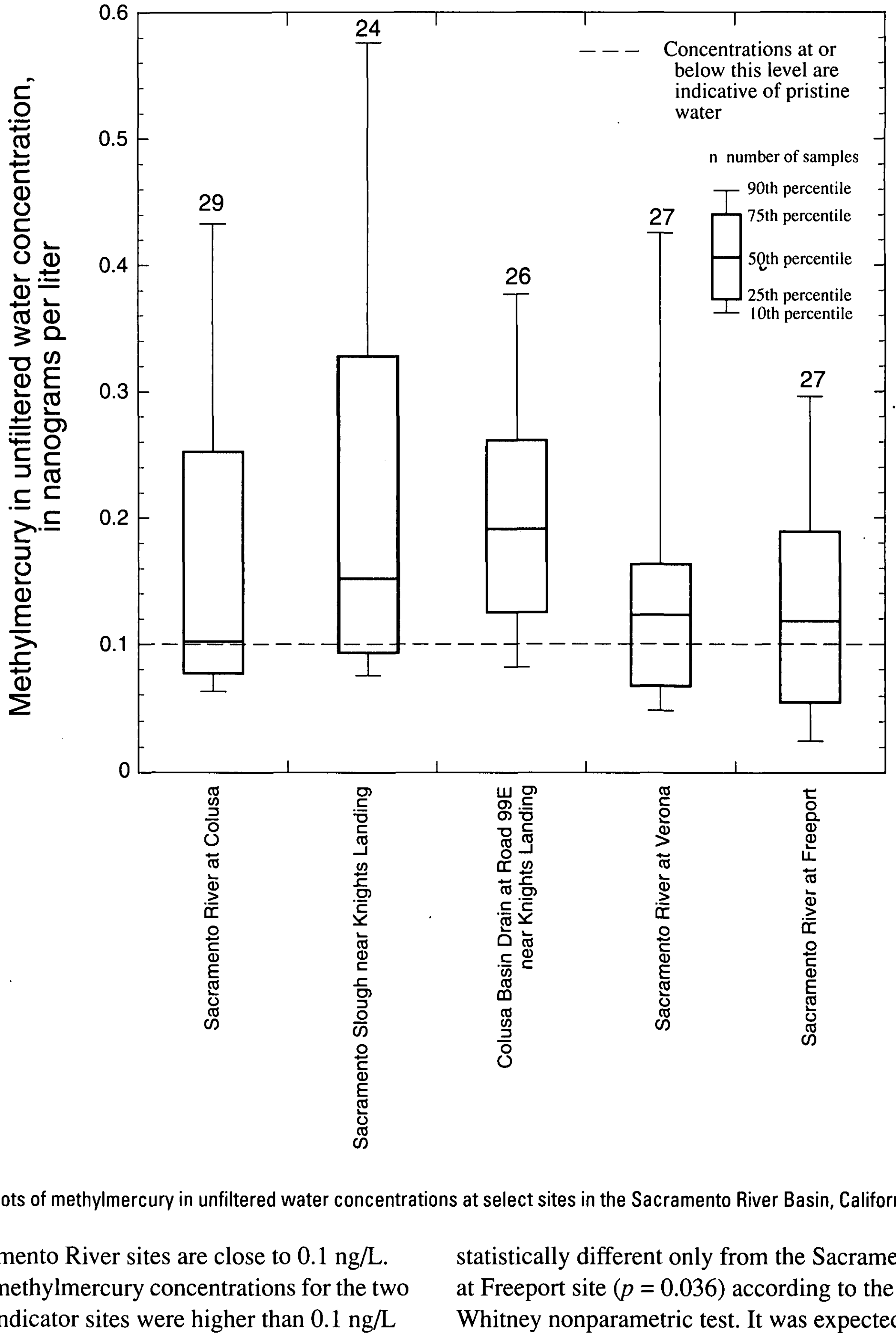


Figure 33. Boxplots of methylmercury in unfiltered water concentrations at select sites in the Sacramento River Basin, California.

for the Sacramento River sites are close to 0.1 ng/L. The median methylmercury concentrations for the two agricultural indicator sites were higher than 0.1 ng/L (the Sacramento Slough near Knights Landing was 0.152 ng/L, and the Colusa Basin Drain at Road 99E near Knights Landing was 0.191 ng/L). Although the highest median concentration was recorded for the Colusa Basin Drain site, that median value is statistically different only from the Sacramento River at Freeport site (*p* = 0.036) according to the Mann–Whitney nonparametric test. It was expected that the median methylmercury concentrations at both agricultural indicator sites would be significantly higher than those for the Sacramento River because of the effects of rice farming, which is the principal agricultural land use in those basins. However, the measured concentrations of sulfate were higher at the Colusa Basin Drain site than at the Sacramento Slough site. The environmental synthesis of methylmercury is thought to be linked to sulfate-reducing bacteria (Zilloux and others, 1993), and therefore, it would be expected that the concentrations of methylmercury would be higher at the Colusa Basin Drain site than at the Sacramento Slough site. Although the median concentration of methylmercury at the Colusa Basin Drain site was slightly higher than that of the Sacramento Slough site, the difference is not statistically significant when tested by the Mann–Whitney nonparametric test of medians. Furthermore, measured concentrations of methylmercury occasionally were higher at the Sacramento Slough site than at the Colusa Basin Drain site. The higher methylmercury concentrations at the Sacramento Slough site may be related to a larger land-surface area that is flooded during the winter in that basin. In summary, although some methylmercury may be produced in rice fields and transported to the agricultural drainage canals, such as the Colusa Basin Drain and the Sacramento Slough, the concentrations are not sufficiently elevated above those already in the Sacramento River to be cause for concern.

There appears to be a seasonal component to methylmercury concentrations for the sites at which methylmercury was measured (fig. 34). The magnitude of the concentrations may also be related to hydrological events. The concentrations were lowest during middle to late summer. Higher concentrations tend to occur during autumn and winter. The highest measured concentrations for the period of this study were during January and February 1997. A significant storm occurred on January 1, 1997, with large amounts of rainfall over much of the Sacramento River Basin, especially over the eastern Sierra Nevada. The high methylmercury concentrations measured during January and February 1997 at these sites can be attributed to that storm. During the El Niño winter of 1997–1998, higher than normal amounts of rain were recorded for much of the Sacramento River Basin, although there was no single storm of the magnitude of the January 1, 1997, storm. As a result, methylmercury concentrations increased during the 1997–1998 winter, but not to the level of the previous winter. The effect of these methylmercury concentrations and the implications for downstream water bodies, such as the San Francisco Bay, have yet to be determined.

Mercury in the Sacramento River is transported to the San Francisco Bay estuary, where further transformations, such as methylation, demethylation, and bioaccumulation, are possible. The hydrological and biogeochemical environment of the estuary is vastly different from that of the Sacramento River and its tributaries because it is tidally influenced, a gradient of fresh to salt water is present, and it includes extensive wetlands. Mercury transported to the estuary will be influenced by the way sediment is redistributed. Some of the fine sediment from the Sacramento River is likely to be transported to wetland environments.

The amount of mercury transported out of the Sacramento River Basin for three winters was calculated by determining the mass at the Yolo Bypass site and the mass at the downstream Sacramento River site at Freeport. The total amount of mercury transported out of the Sacramento River Basin during the winter of 1996–1997 was calculated to be 487 kg, most of which was associated with the flood of January 1, 1997. Despite the flood, the amount of rainfall in the Sacramento River Basin during that winter was less than average. During the flood, mercury samples were collected along a reach of the Sacramento River from below Shasta Lake to the Yolo Bypass site. The sampling design approximated Lagrangian conditions on the Sacramento River. A Lagrangian sampling requires that samples be collected according to a moving frame of reference. Once the first water sample is collected, the next sample is collected at the downstream location consistent with the river velocity, such that the same approximate parcel of water is resampled. Predetermined sites on the Sacramento River were selected for sampling, and thus the time of sample collection had to be consistent with the approximate Lagrangian timeframe. The discharge of mercury from the Sacramento River was on the order of 32 kg/d during maximum river flow. Of that amount, approximately 75 percent of the mercury load was attributable to the reach between the Sacramento River above Bend Bridge near Red Bluff and the Sacramento River at Colusa. That reach is above the confluence of the Sacramento and Feather rivers and, therefore, the streams draining the gold mining region were not the principal source of mercury in spite of the high precipitation over the gold country region.

During the winter of 1997–1998, El Niño conditions resulted in precipitation amounts that were higher throughout much of the Sacramento River Basin in relation to non-El Niño years, and the Yolo

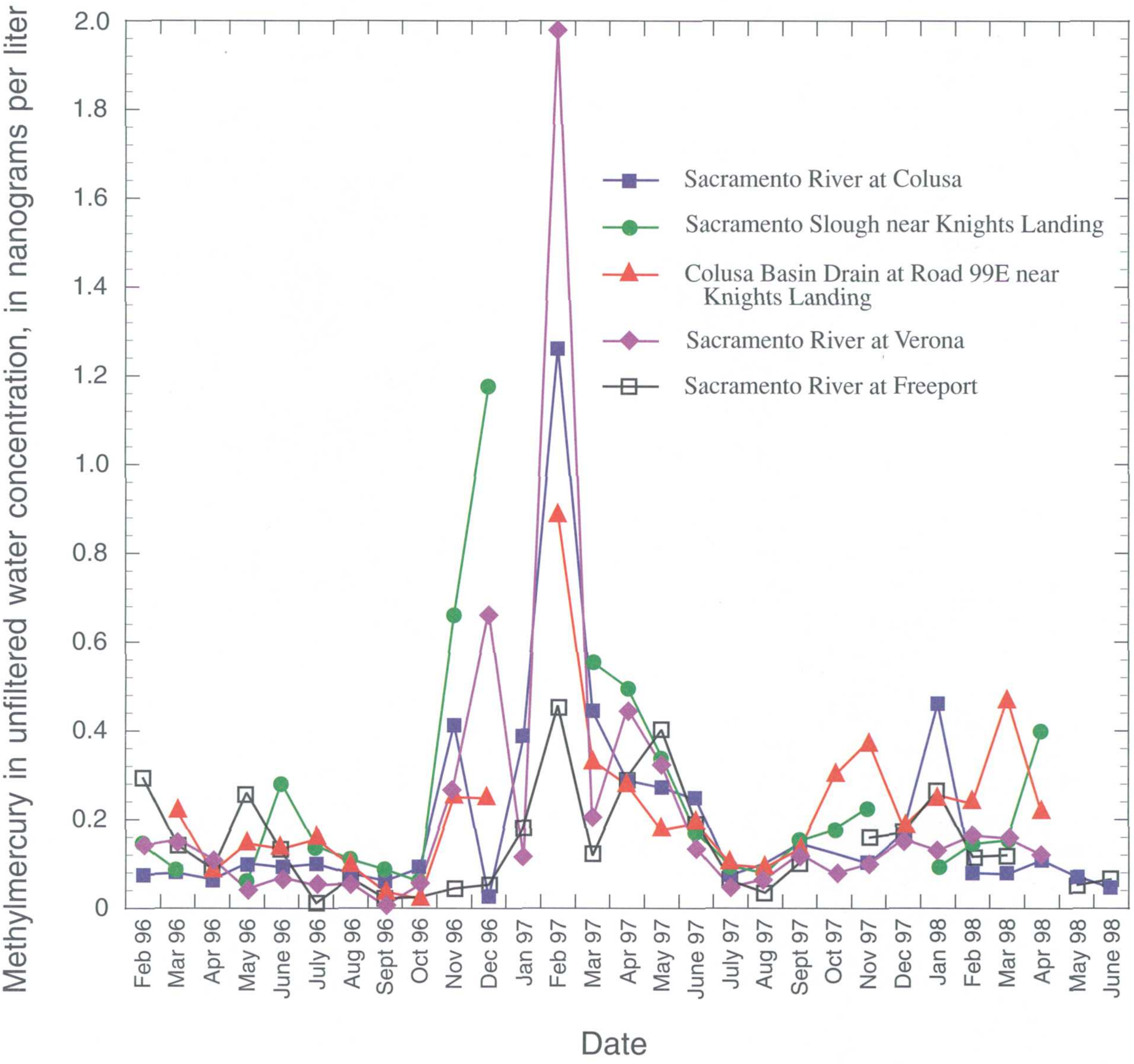


Figure 34. Time series plot of methylmercury in unfiltered water concentrations at select sites in the Sacramento River Basin, California. A discontinuous line indicates no samples collected during those months.

Bypass was used as a flood control channel for a longer period. The total amount of mercury transported out of the Sacramento River Basin during that winter was calculated to be 506 kg. The winter of 1998–1999 was different from the previous two winters in that precipitation in the Sacramento Valley was lower than average, but precipitation in the Sierra Nevada was higher than average. Because of the lower than normal amounts of precipitation in the Sacramento Valley, the Yolo Bypass was not needed for flood control and, as a result, much less water was transported out of the basin through the bypass. The total amount of mercury transported out of the basin during the winter of 1998–1999 was calculated to be 169 kg. Previous work by Foe and Croyle (1999) has shown that the amount of mercury transported out of the Sacramento River Basin can be as high as 800 kg/yr. That measurement was made in the timeframe from May 1, 1994, through April 30, 1995, and most of the mass was transported during the winter rainy season.

The mass of methylmercury transported out of the Sacramento River Basin could not be calculated because only a relatively few samples were collected at the Yolo Bypass; therefore, the variability in concentrations at that site is unknown. Instantaneous loads could be calculated for the site on the Sacramento River at Verona, which is just downstream from the confluence with the Feather River and downstream from the agricultural tributaries. That site, because of its proximity to the agricultural streams and the Feather River, may have some of the highest methylmercury concentrations of any Sacramento River site. Methylmercury loads in the Sacramento River at Verona are lowest during late spring through autumn. Methylmercury loads range from nearly 10 to less than 1 g/d. The highest loadings occurred during the winter of 1996–1997. The greatest load during that period was 282 g/d calculated for a sample collected during February 1997. The load decreased to 8 g/d in March in response to lower amounts of rainfall. Methylmercury loadings were more consistent in the subsequent El Niño winter of 1997–1998. Methylmercury loads increased from 8 g/d in December 1997 to 20 g/d in January, and remained at levels of 28 and 24 g/d in February and March, respectively. Loads decreased to 10 g/d in April. Further work would be necessary to determine the actual loads of methylmercury transported from the Yolo Bypass and how the contribution of methylmercury to the San Francisco Bay Estuary from the Sacramento River Basin compares with the amount produced within the estuary system.

SUMMARY AND CONCLUSIONS

Water-quality conditions were characterized at 12 sites in the Sacramento River Basin between February 1996 through April 1998. During this time, two unusual hydrological events affected the discharge and quality of water in the Sacramento River Basin. The first was a major flood that occurred on or close to January 1, 1997. Although high rainfall amounts were recorded throughout the Sacramento River Basin, the Sierra Nevada part of the basin received the highest amounts of precipitation. The second event was the El Niño winter of 1997–1998, when greater than normal amounts of precipitation were recorded throughout the Sacramento River Basin. During both winters, elevated concentrations of mercury, above the water-quality criteria for the protection of aquatic life, were measured in the Sacramento River and in tributaries to the Sacramento River. The sources of the mercury were determined to be Cache Creek and streams that drain the Sierra Nevada, as well as an unknown source located somewhere in the upper Sacramento Valley or foothills of the Middle Cascade Mountains. The unknown source was contributing some of the greatest loads of mercury to the Sacramento River.

Water quality of the Sacramento River is generally good during spring through autumn because most of the water is from reservoirs located in the mountainous parts of the basin. The water in the reservoirs, which is mainly from melting snow, is generally characterized by low specific conductance, low nutrient concentrations, and low dissolved and suspended organic carbon concentrations.

Water quality of the Sacramento River and major tributaries can be degraded by agricultural runoff. Most of the agricultural drainage enters the Sacramento River just upstream from the Verona sampling site. Rice is one of the principal crops of the Sacramento Valley, and drainage from rice fields enters the Sacramento River from April through September. Concentrations of nutrients from this runoff are diluted upon mixing with the Sacramento River water. Some elevated concentrations of methylmercury were detected in water from one agricultural drainage system. However, those concentrations were only slightly higher than concentrations of methylmercury already present in the Sacramento River, and they do not represent a significant source of methylmercury to the Sacramento River.

Temperature of the Sacramento River is of concern for the well-being of migrating fish such as salmon. Temperature of the Sacramento River rises rapidly in early April through May, especially at the site near Colusa, Calif. Temperature maintenance of the Sacramento River for migrating salmon is generally not a problem during high water years, but can be difficult during drought years.

The concentrations of trace elements, including mercury, were always below any existing drinking water standards. Mercury concentrations frequently exceeded the standards for the protection of aquatic life, and the exceedances always happened during the late fall to early spring rainy season.

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