ENVIRONMENTAL SETTING OF THE SAN JOAQUIN–TULARE BASINS, CALIFORNIA

by Jo Ann M. Gronberg, Neil M. Dubrovsky, Charles R. Kratzer, Joseph L. Domagalski, Larry R. Brown, *and* Karen R. Burow

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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
Chief Hydrologist

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per month (acre-ft/mo)	0.001233	cubic hectometer per month
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	2.540	centimeter
inch (in.)	25.4	millimeter
inch per year (in./yr)	2.540	centimeter per year
mile (mi)	1.609	kilometer
gallon per day (gal/d)	0.003785	cubic meter per day
pound, avoirdupois (lb)	0.4536	kilogram
pound per acre (lb/acre)	1.1208	kilogram per hectare
square mile (mi^2)	2.590	square kilometer

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation: °F=1.8(°C)+32

Vertical Datum

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

Abbreviations

BOR, Bureau of Reclamation
DWR, California Department of Water Resources
GIRAS, Geographic Information Retrieval and Analysis System
lb a.i., pound(s) active ingredient
NAWQA, National Water-Quality Assessment Program
NPDES, National Pollutant Discharge Elimination System
USGS, U.S. Geological Survey

Environmental Setting of the San Joaquin–Tulare Basins, California

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Abstract

The National Water-Quality Assessment Program for the San Joaquin–Tulare Basins began in 1991 to study the effects of natural and anthropogenic influences on the quality of ground water, surface water, biology, and ecology. The San Joaquin–Tulare Basins study unit, which covers approximately 31,200 square miles in central California, is made up of the San Joaquin Valley, the eastern slope of the Coast Ranges to the west, and the western slope of the Sierra Nevada to the east. The sediments of the San Joaquin Valley can be divided into alluvial fans and basin deposits.

The San Joaquin River receives water from tributaries draining the Sierra Nevada and Coast Ranges, and except for streams discharging directly to the Sacramento–San Joaquin Delta, is the only surface-water outlet from the study unit. The surface-water hydrology of the San Joaquin–Tulare Basins study unit has been significantly modified by development of water resources. Almost every major river entering the valley from the Sierra Nevada has one or more reservoirs. Almost every tributary and drainage into the San Joaquin River has been altered by a network of canals, drains, and wasteways.

The Sierra Nevada is predominantly forested, and the Coast Ranges and the foothills of the Sierra Nevada are predominately rangeland. The San Joaquin Valley is dominated by agriculture, which utilized approximately 14.7 million acre-feet of water and 597 million pounds active ingredient of nitrogen and phosphorus fertilizers in 1990, and 88 million pounds active ingredient of pesticides in 1991. In addition, the livestock industry contributed 318 million pounds active ingredient of nitrogen and phosphorus from manure in 1987.

This report provides the background information to assess the influence of these and other factors on water quality and to provide the foundation for the design and interpretation of all spatial data. These characterizations provide a basis for comparing the influences of human activities among basins and specific land use settings, as well as within and among study units at the national level.

THE NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

In 1991, the U.S. Geological Survey (USGS) began full implementation of the National Water-Quality Assessment (NAWQA) Program. The goals of the NAWQA Program are to: (1) describe current water-quality conditions for a large part of the nation's freshwater streams, rivers, and aquifers; (2) describe how water quality is changing over time; and (3) improve understanding of the primary natural and human factors that affect water-quality conditions (Hirsch and others, 1988).

The primary building blocks of the NAWQA Program are the study-unit investigations. The study units are regional hydrologic systems that include parts of most major river basins and aquifer systems of the United States (fig. 1). The study units cover areas of 1,200 to more than 65,000 square miles (mi^2) and incorporate about 60 to 70 percent of the nation's

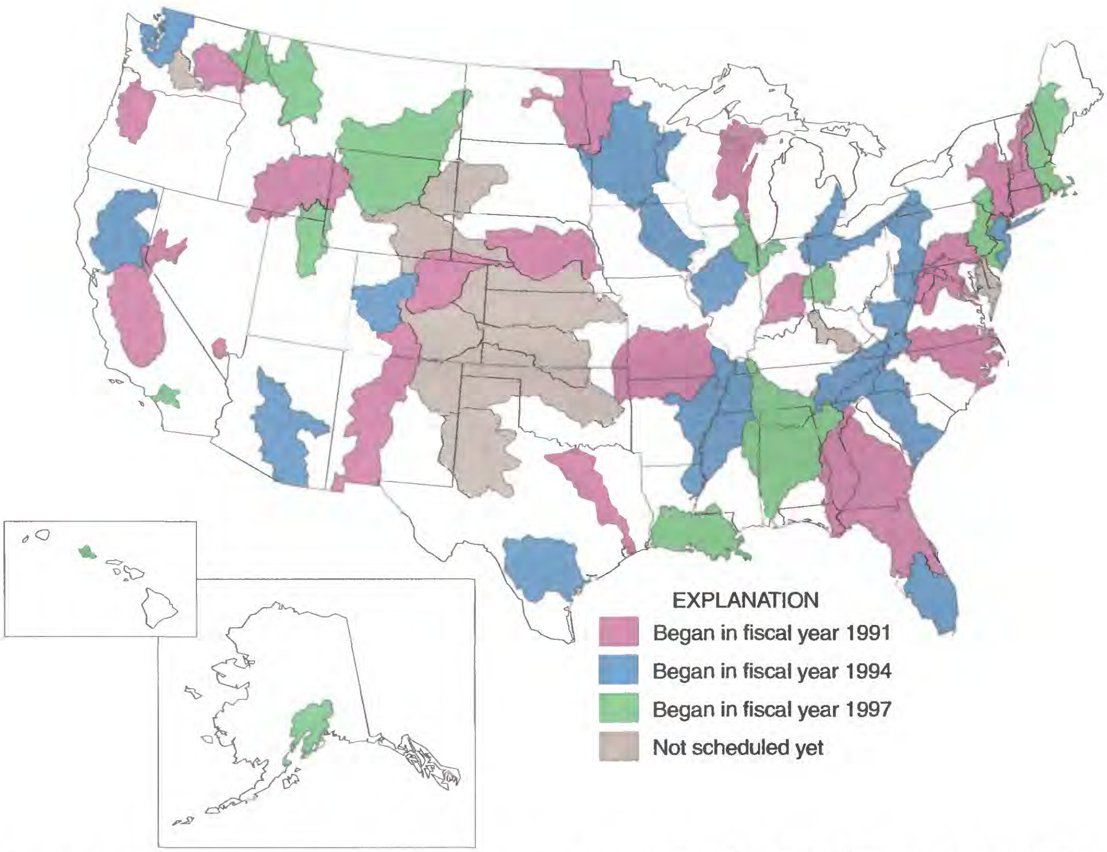

Figure 1. Study units of the National Water-Quality Assessment Program (modified from Gilliom and others, 1995, figure 1).

water use and population served by public water supply. The San Joaquin–Tulare Basins study unit was one of twenty studies that began assessment activities in 1991. An additional 16 study-unit investigations began in autumn 1994, and the final set of 13 study-unit investigations began in autumn 1997. Ten study-unit investigations have not yet been scheduled. Intensive assessment activities in each of the study units are being done on a rotational rather than a continuous basis, with about one-third of the study units being studied intensively at any given time (fig 2). For each study unit, 3- to 5-year periods of intensive data collection and analysis will be alternated with 5- to 6-year periods of less intensive study and monitoring.

A major design feature of the NAWQA Program is the integration of water-quality information at a wide range of spatial scales, both within and among study units. In particular, data from the study-unit investigations will provide the basis for regional and national-level assessments. To facilitate this regional and national synthesis of data, all study units will use consistent approaches and methods. In keeping with extensive input from local, state, and Federal agencies and other organizations and the widespread recognition of the contribution of some agricultural activities to water-quality problems, the first national syntheses will address pesticides and nutrients in the nation's water resources.

The purpose of this report is to describe the environmental setting of the San Joaquin–Tulare Basins study unit, and to describe the major factors affecting water quality in the study unit. This report provides the background information to describe and explain the water-quality conditions and to link the study unit to the national program. This report, along with the other studies conducted as part of NAWQA, will be important to water-resources managers, planners, and policy makers for strong and unbiased decision-making. Information from NAWQA will contribute to the process of improving the nation's water quality by guiding research, monitoring, and regulating activities.

In addition to the national assessments, the study-unit investigations will address local water-quality problems. These issues will be selected through consultation with a committee of interested parties from all levels of government and the private sector who are concerned with water management in the study unit. Because of the heavily agricultural

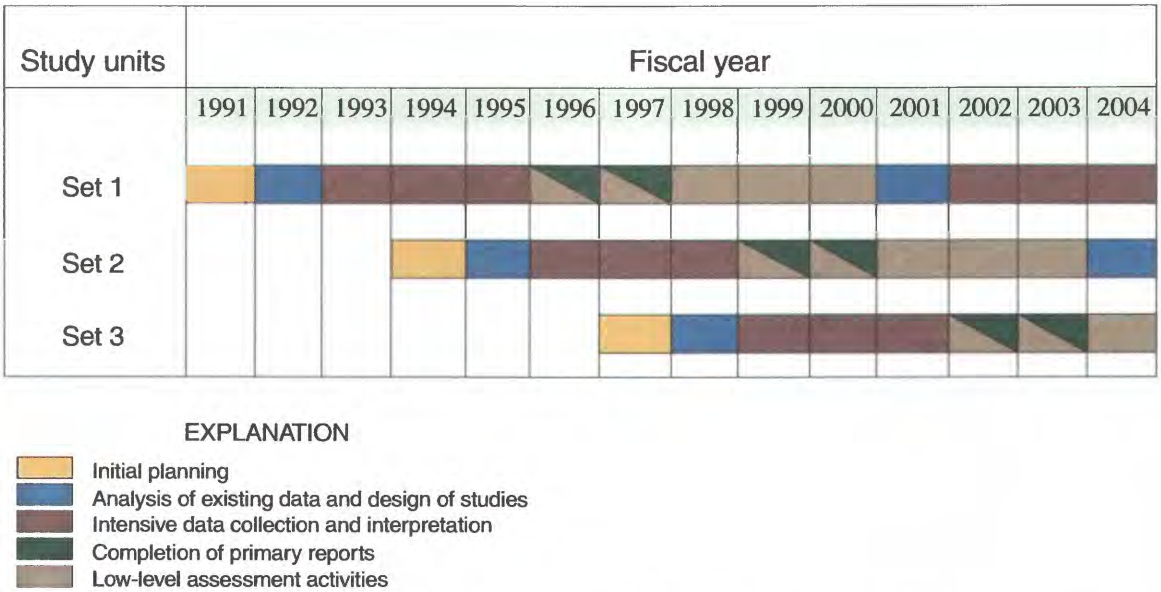

Figure 2. Timetable for the first decade cycle of the National Water-Quality Assessment Program.

nature of the San Joaquin–Tulare Basins study unit, local issues parallel the subjects of the national assessment to a large extent. The San Joaquin–Tulare Basins NAWQA Liaison Committee consists of members from the following county, state, federal, and private agencies:

- Aquatic Habitat Institute
- Bureau of Reclamation, Mid Pacific Region
- California Department of Fish and Game
- California Department of Food and Agriculture, Agriculture Resources Board
- California Department of Health Services, Office of Drinking Water
- California Department of Pesticide Regulation, Environmental Monitoring Branch
- California Department of Water Resources
- California Regional Water Quality Control Board, Central Valley Region
- California State Water Resources Control Board
- California State University, Fresno, School of Engineering
- California Waterfowl Association
- Environmental Defense Fund
- Kenneth D. Schmidt and Associates, Groundwater Quality Consultants
- Kern County Water Agency
- Kings River Conservation District
- Larry Walker Associates, Inc., Environmental Engineering and Management
- Merced County Association of Governments
- Merced County Department of Agriculture
- Merced Irrigation District
- Metropolitan Water District of Southern California
- Modesto Irrigation District
- National Park Service
- San Joaquin River Flood Control Association
- San Luis and Delta–Mendota Water Authority
- Stanford University, Department of Engineering and Environmental Sciences
- Turlock Irrigation District
- United Anglers of California
- U.S. Army Corps of Engineers
- U.S. Department of Agriculture, Water Management Research Laboratory
- U.S. Environmental Protection Agency
- U.S. Fish and Wildlife Service
- U.S. Natural Resources Conservation Service
- University of California, Farm and Home Advisors Office
- University of California, Davis, Department of Land, Air, and Water Resources
- Water Resources Center
- Westlands Water District

SAN JOAQUIN–TULARE BASINS

Location and Physiography

The San Joaquin–Tulare Basins study unit covers approximately 31,200 mi^2 in central California. The study unit includes the western slope of the Sierra Nevada to the east, the San Joaquin Valley, and the eastern slope of the Coast Ranges to the west (fig. 3). The study unit can be separated into the San Joaquin

Figure 3. San Joaquin–Tulare Basins, California, study unit.

Basin to the north and the hydrologically closed Tulare Basin to the south. Altitude ranges from near sea level in the San Joaquin Valley to a maximum altitude of 14,495 feet (ft) above sea level at Mount Whitney, the highest point in the conterminous United States. The San Joaquin Valley is a monotonously flat structural basin bounded by the Sierra Nevada to the east, the Coast Ranges to the west, the Tehachapi Mountains to the south, and the Sacramento–San Joaquin Delta to the north. The crests of the Coast Ranges are about 3,000 to 5,000 ft, the Tehachapi Mountains, about 5,000 to 8,000 ft, and the Sierra Nevada, about 8,000 to 14,000 ft. Land-surface altitude of the valley rises from near sea level to about 1,000 ft at the top of the dissected older alluvium in the southeast.

The boundary of the study unit is defined by the drainage divides of the Sierra Nevada, Coast Ranges, and Tehachapi Mountains on the east, west and south, respectively, and by the boundary of the Sacramento–San Joaquin Delta to the north. Assessment of the delta would require an understanding of both the complex hydrodynamics of the delta system (Smith and others, 1995) and the water quality of all the rivers feeding into it, which are beyond the scope of this study. This information should be available when the current USGS studies in the delta system, and the Sacramento Valley NAWQA, which began in autumn 1994, are completed. In addition, specific aspects of the distribution, transport, and fate of pesticides in the delta are being studied as part of the USGS Toxic Substances Hydrology Program (Kuivila and Nichols, 1991) as well as by state agencies. The area north of the Stanislaus River that drains directly to the delta does not affect the water quality of the San Joaquin River and will be monitored at a lower level. Exclusion of the delta is also in keeping with the National Academy of Sciences conclusion that NAWQA not include study of estuaries at this time (National Research Council, 1990, p. 7).

Geology

The San Joaquin and Tulare Basins constitute the southern two-thirds of the Central Valley of California, which is part of a large, northwest-trending, asymmetric structural trough, filled with marine and continental sediments up to 6 miles (mi) thick (fig. 4). The bedrock geology of the areas adjacent to the east and west sides of the San Joaquin Valley contrasts sharply. To the east of the valley, the Sierra Nevada is composed primarily of pre-Tertiary granitic rocks and is separated from the valley by a foothill belt of Mesozoic and Paleozoic marine rocks and Mesozoic metavolcanic rocks along the northern one-third of the boundary (California Division of Mines and Geology, 1958; 1959; 1964; 1965a,b; 1966; 1967; 1969). The Coast Ranges west of the valley have a core of Franciscan assemblage of late Jurassic to late Cretaceous or Paleocene age and Mesozoic ultramafic rocks. These rocks are overlain by marine and continental sediments of Cretaceous to Quaternary age and some Tertiary volcanic rocks.

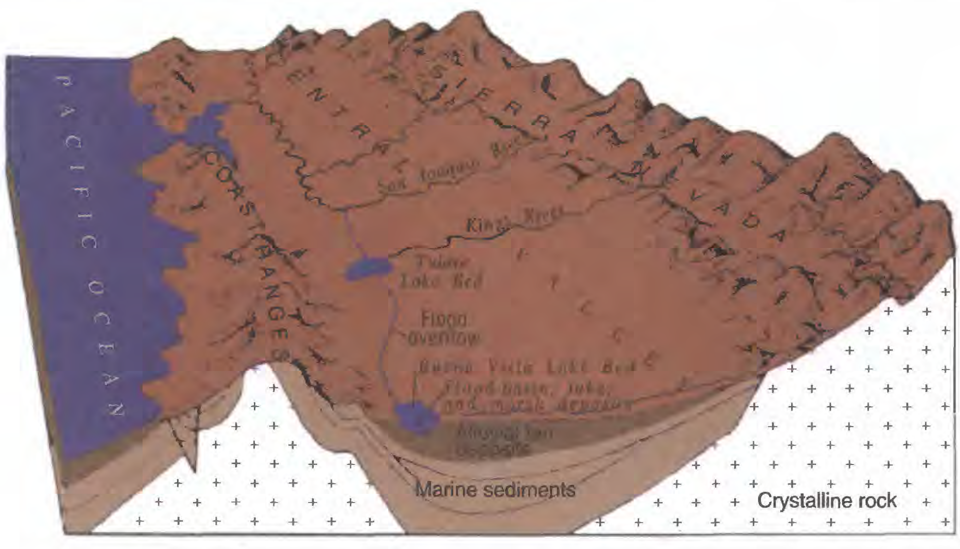

Figure 4. Generalized geologic section and view of part of the Central Valley, California (from Page, 1986).

This contrast between the composition of the highlands on the east and west sides of the valley has a profound influence on the sediments and water quality in the valley. The composition of the sediments of the San Joaquin Valley, shown in the map of generalized surficial geology (fig. 5), reflect their source area and manner of deposition. Alluvial, Pleistocene non-marine, and other nonmarine deposits of the eastern part of the valley were derived primarily from the weathering of granitic intrusive rocks of the Sierra Nevada, with lesser contributions from the sedimentary and metasedimentary rocks of the foothills. In the eastern part of the valley, sediments derived primarily from the Sierra Nevada are highly permeable, medium- to coarse-grained sands with low total organic carbon, forming broad alluvial fans where the streams enter the valley. These deposits generally are coarsest near the upper parts of the alluvial fans and finest near the valley trough. Dune sand consists of well-sorted medium- to-fine sand, as much as 140 ft thick (Page, 1986). The alluvial deposits of the western part of the valley tend to be of finer texture relative to those of the eastern part of the valley because they are derived from the Coast Ranges and have a higher clay content. Detailed analysis of the Coast Ranges alluvium in western Fresno County indicates that the alluvium is coarsest in the upper parts of the alluvial fans and finer, mainly silt and clay, in the middle and lower parts of the fans and in the valley trough (Laudon and Belitz, 1991). The Tulare Lake bed (figs. 4 and 5) is underlain by as much as 3,600 ft of primarily fine-grained lacustrine and marsh deposits (Page, 1986).

Stream-channel deposits of coarse sand occur along the San Joaquin River and its major east side tributaries. In the valley trough, the stream-channel deposits are flanked by basin deposits of varying extent. The basin deposits are interbedded lacustrine, marsh, overbank, and stream-channel sediments deposited by the numerous sloughs and meanders of the major rivers. The soils that have developed on these deposits generally have a high clay content and low permeability (Davis and others, 1959).

Climate

The San Joaquin Valley has an arid-to-semiarid climate that is characterized by hot summers and mild winters. The eastern slopes of the Coast Ranges and the valley are in the rain shadow of the Coast Ranges. Warm, moist air masses from the Pacific Ocean are forced aloft by the Sierra Nevada. The air masses cool, and the moisture condenses, resulting in heavy precipitation on the western slopes. This precipitation, occurring both as rainfall and snow, is the major source of water entering the basin.

Mean annual precipitation (1911–1960) on the valley floor ranges from less than 5 inches (in.) in the south to 15 in. in the north (fig. 6). Average annual precipitation in the Sierra Nevada, mostly in the form of snow, ranges from about 20 in. in the lower foothills to more than 80 in. at some higher altitude sites. Precipitation in the Coast Ranges varies from less than 10 in. to more than 20 in. (Rantz, 1969). As in the valley, precipitation in the Sierra Nevada and Coast Ranges increases from south to north. Annual precipitation in the study unit is highly variable, as shown at three long-term stations (fig. 7). The 1987–1992 drought in California resulted from below-normal precipitation.

The seasonal distribution of precipitation in the study unit is illustrated for the same stations by bar-charts showing the mean monthly precipitation at each station for 1950–1991 (fig. 7). These stations show that more than 80 percent of the annual precipitation falls during November through April; generally January is the peak precipitation month. Potential evapotranspiration can be as much as 49 inches per year (in./yr) (Bertoldi and others, 1991).

Natural Hydrology and Native Habitats

The pre-European San Joaquin and Tulare Basins supported rich and diverse natural communities. Aquatic habitats included sloughs, creeks, rivers, lakes, ponds, and permanent wetlands and their associated plants and animals. Terrestrial habitats included seasonal wetlands, riparian forest, valley oak savanna, California prairie, and San Joaquin saltbush communities in the valley, and ponderosa pine and lodgepole pine forests in the Sierra Nevada. Valley floor communities are shown in figure 8. Early explorers and settlers clearly described the large populations of fishes, mammals, and birds associated with various natural habitats (San Joaquin Valley Drainage Program, 1990a). These habitats were so productive that they were believed to have supported the largest population of nonagricultural Native Americans in North America (Latta, 1949; Kroeber, 1961).

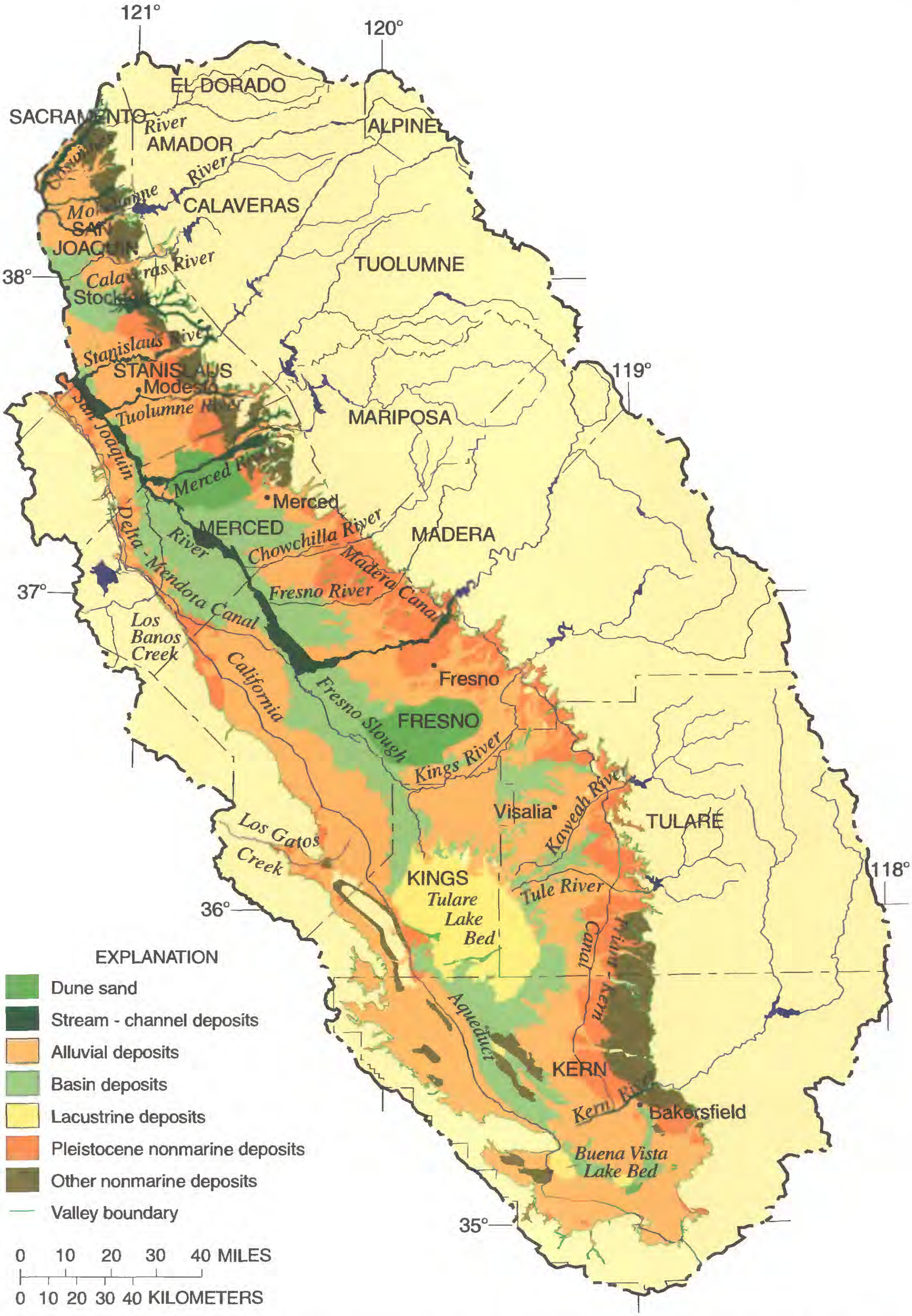

Figure 5. Generalized surficial geology of the San Joaquin Valley, California (California Division of Mines and Geology, 1958; 1959; 1964; 1965a,b; 1966; 1967; 1969).

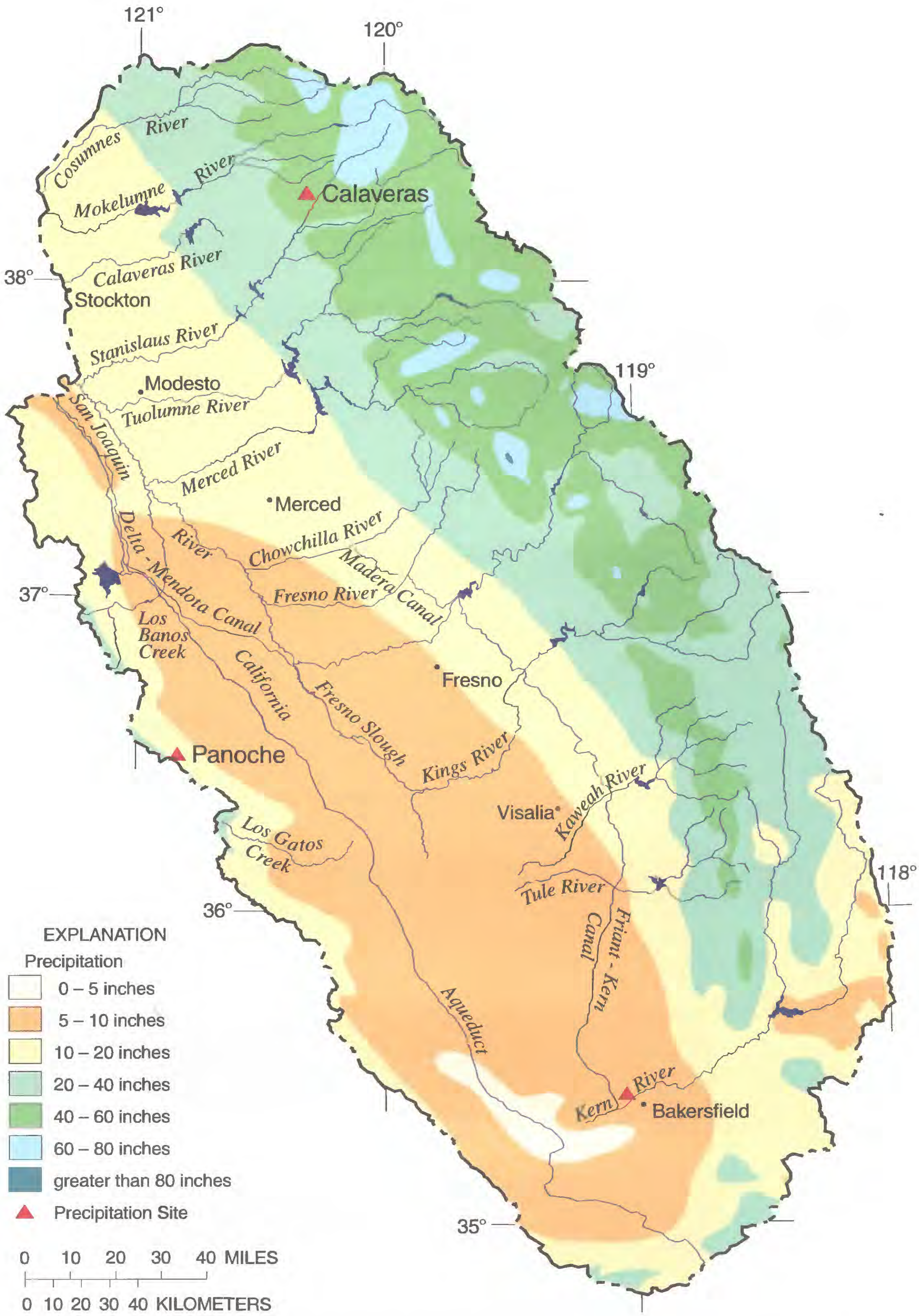

Figure 6. Spatial distribution of mean annual precipitation in the San Joaquin–Tulare Basins, California, study unit, 1911–1960 (modified from Rantz, 1969).

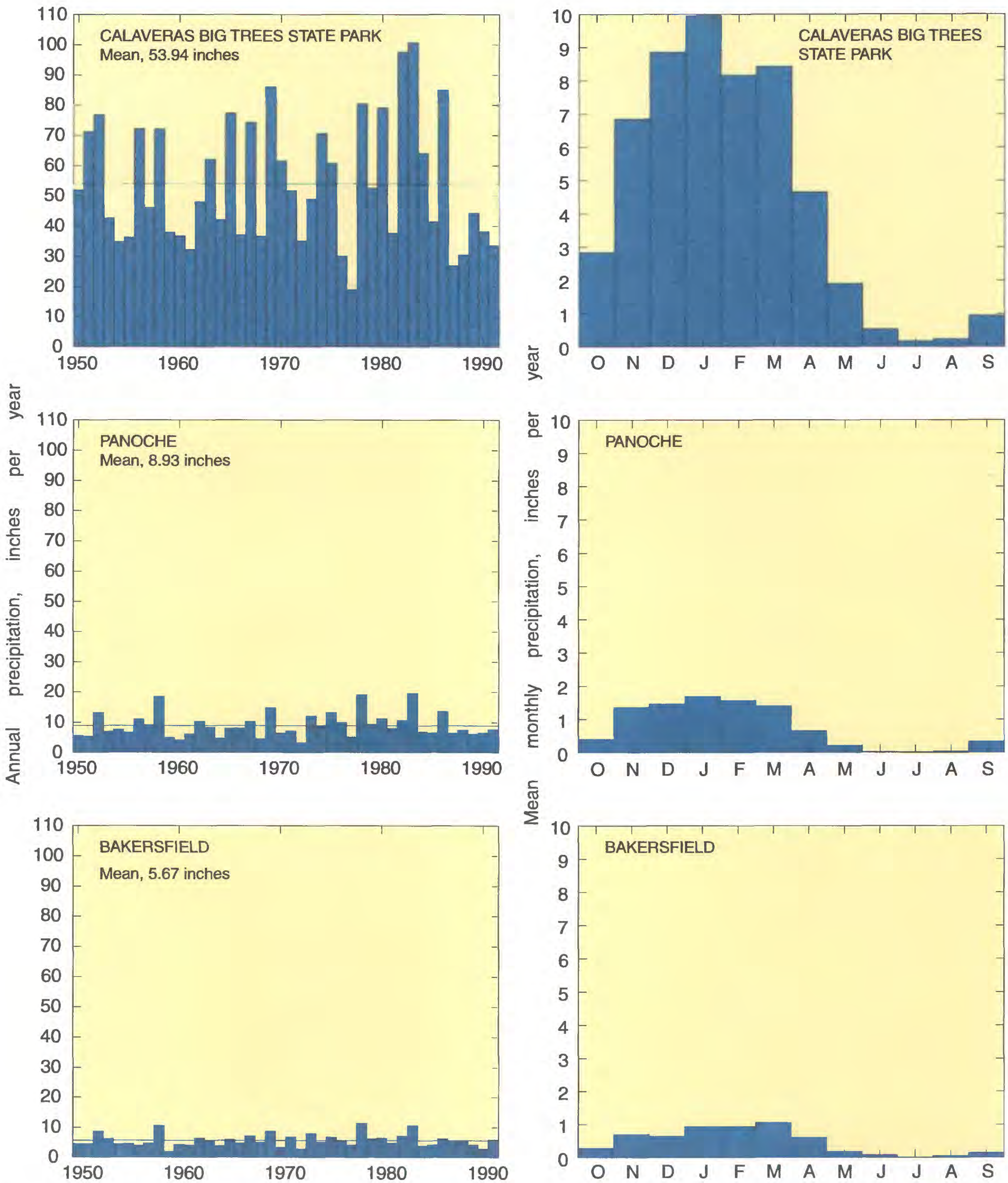

Figure 7. Annual and mean monthly precipitation at three selected stations in the San Joaquin–Tulare Basins, California, study unit, 1950–1991.

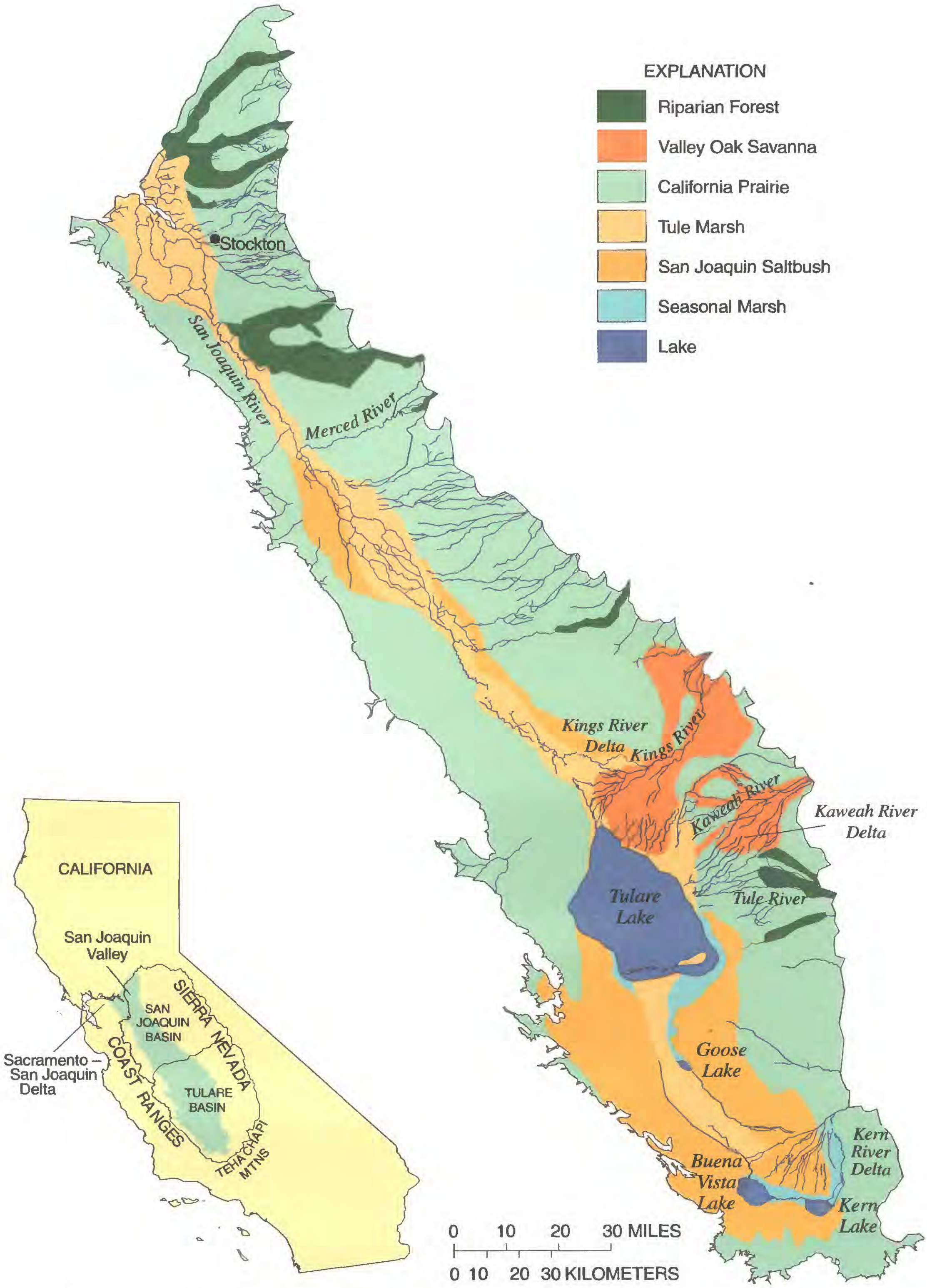

Figure 8. Natural hydrology and native habitats of the San Joaquin Valley, California (San Joaquin Valley Drainage Program, 1990a, figures 2-1 and 2-2).

The productivity of the system was linked to the natural hydrology of the valley. In the San Joaquin Basin, the San Joaquin River formed natural levees north of the confluence with the Merced River, but at high flows, the river would flood the land south of the Merced River, forming large freshwater marshes on the valley floor (Katibah, 1984; Warner and Hendrix, 1985). Additional areas of wetlands created by San Joaquin River overflow were in the area near Stockton (San Joaquin Valley Drainage Program, 1990a). The semiclosed Tulare Basin in the south was dominated by four large, shallow, and largely temporary inland lakes. The largest and most northerly was Tulare Lake, which received water from the Kings, Kaweah and Tule Rivers. Goose Lake was south of Tulare Lake. Buena Vista Lake and Kern Lake were formed by the Kern River.

As agricultural activities expanded in the valley, wetlands and riparian forests were drained, cleared, and converted to agricultural land (table 1). The remnant wetlands in the study unit are less than 8 percent of the wetland acreage before settlement of the San Joaquin Valley in the 19th century (San Joaquin Valley Drainage Program, 1990a). Wetland areas now include public lands managed by State and Federal agencies, and privately-owned duck clubs.

Ecology

Ecoregions

The study unit includes parts of five U.S. Environmental Protection Agency ecoregions (fig. 9), which are based on perceived patterns of combined causal and integrative factors including land-surface forms, potential natural vegetation, land use, and soils (Omernik, 1987). The major parts of the study unit are in the Sierra Nevada, Southern and Central California Plains and Hills, and Central California Valley ecoregions. The Sierra Nevada ecoregion is characterized by high mountains of mixed conifer forest (fir, pine, Douglas-fir), red fir forest, and lodgepole pine/subalpine forest (hemlock). Land use is forest (logging) and woodland grazing, and soils are classified as Ultisols (Xerults). The Southern and Central California Plains and Hills ecoregion is characterized by low mountains, tablelands of moderate to considerable relief, and irregular plains. Natural vegetation is oak woodlands (valley and blue oak), chaparral (manzanita, ceanothus), and California steppe (needlegrass). Land use is open woodland grazing, and the soils are light-colored of subhumid regions. Finally, the Central Valley ecoregion of California is characterized by flat plains. The natural vegetation of California steppe (needlegrass), tule marshes (bulrush, cattails), mostly has been replaced by irrigated agriculture, other crop-land, and grazing land. Soils are recent alluvial soils, light-colored soils of the wet and dry subhumid regions.

Aquatic Biology

The fishes are the most studied group of aquatic organisms in the study unit, whereas knowledge of the benthic macroinvertebrates and algae is minimal. Fortunately, patterns in the fish fauna illustrate the complexities in aquatic biology in relation to the diverse habitats that were present historically and the changes that have affected those habitats in both evolutionary and historical times. The diverse aquatic habitats in the study unit include small alpine streams in the Sierra Nevada, the large Sierra Nevada tributaries, the lower San Joaquin River, and small intermittent streams in the Coast Ranges and Sierra Nevada foothills that remain isolated from larger streams except during the largest floods. Imposed on this natural complexity are agricultural and urban development, and the introduction of exotic species of fish, invertebrates, and plants.

The original fish fauna of the San Joaquin Valley included 19 of the 34 species native to the Sacramento–San Joaquin drainage system and 12 of the 17 endemic forms, found nowhere else in the world (Moyle, 1976; Moyle and Williams 1990). The ecology of the native fishes is dominated by altitude, stream gradient, stream order (size), and the physical aspects of the aquatic environment that are correlated with these features. In particular, water temperature, discharge, depth, substrate, and turbidity are important determinants of fish distribution in the San Joaquin Valley and other areas of the Sacramento–San Joaquin drainage (Moyle and Nichols, 1973; Moyle and others, 1982; Brown and Moyle, 1987). The individual responses of fishes to these physical factors result in patterns of co-occurrence among species that can be summarized as different fish assemblages or associations. In the San Joaquin Valley, four fish associations have been identified (Moyle and Nichols, 1973; Moyle, 1976; Brown and Moyle, 1987), each associated with particular combinations of physical habitat characteristics (table 2).

Table 1. Historical and current acreage of native plant communities of the San Joaquin Valley, California

[Data from Brown, 1996. <, less than][1]

Native plant community	Acreage		
	Historical	Current	Percentage of historic community remaining
Wetland	1,093,000	[1]85,274-90,749	8
Riparian Forest	400,000	[2]35,360	9
Valley Oak Savanna	502,000	[2]3,933	<1
California Prairie	4,444,000	[3]1,500	<1
San Joaquin Saltbush	1,172,000	[4]99,381	8

[1]Acreages from San Joaquin Valley Drainage Program (1990*a*) table 2-6, "Changes in Wetland Habitat Acreage: 1957-63 through 1986-89." Acreages do not include wetlands in the south delta and Farmington-Escalon duck club areas; therefore, acreage estimate may be low.

[2]Adapted by San Joaquin Valley Drainage Program (1990a) from data generated through photo-interpretation of 1977 aerial photographs (Katibah and others, 1980). Data were not available for all areas of the San Joaquin Valley; therefore, acreage estimate may be low. Conversely, current acreage probably has been reduced by suburban and/or other developments since 1977.

[3]Current acreage represents remnants of native prairie dominated by perennial bunchgrasses as of 1972 (Barry, 1972).

[4]Estimate, based on habitat remaining in the Tulare Basin, may be low (Werschkull and others, 1984).

The rainbow trout assemblage occurs at high altitudes and is associated with clear headwater streams with a steep gradient. These streams are perennial with swift moving waters, abundant riffles, cold water temperatures, and high concentrations of dissolved oxygen. The dominant species is rainbow trout.

As the gradient decreases and water temperatures increase, the rainbow trout assemblage blends into the squawfish-sucker-hardhead assemblage. In the San Joaquin Valley, this assemblage is largely restricted to an altitudinal band from about 100 to 1,500 ft above sea level. The streams in this area are characterized by deep, rocky pools, shallow riffles, and minimum summertime flows as low as 0.2 cubic feet per second (ft^3/s). This assemblage is dominated by Sacramento squawfish, Sacramento suckers, and hardhead.

On the valley floor the squawfish-sucker-hardhead assemblage grades into the deep-bodied fish assemblage, characterized by large flat open channels and backwaters, which are warmer and turbid. Before large-scale water development and habitat modifications, this assemblage was dominated by Sacramento perch, thicktail chub, hitch, tule perch, blackfish, and splittail. Large suckers and squawfish also were present. Only blackfish remain; the other species have been replaced by a wide variety of introduced fishes.

The small intermittent tributaries to the larger streams are characterized by the California roach assemblage. These streams have intermittent summer flows and water temperatures that may exceed 86°F in isolated pools. The dominant species is the California roach, which is tolerant of the high temperatures and occasionally low oxygen concentrations (Cech and others, 1990).

The negative effects of historical changes in land and water use on aquatic biota are most evident when considering the status of chinook salmon populations in the study unit. The population of historical salmon runs in the San Joaquin River drainage before the large-scale water development and habitat modifications was estimated at 300,000 to 500,000 fish (Lufkin, 1991). In 1989–1990 less than 3,500 salmon were present in the drainage (California Department of Fish and Game, 1991). Spring-run chinook salmon, at one time dominant in the system, were eradicated when dams denied them access to cold water pools in upstream areas where they over-summered before spawning in the fall. Fall-run chinook salmon are now the only remaining race of salmon in the study unit.

The lack of historical data on invertebrate and algal populations makes it difficult to determine if changes have taken place. However, it seems likely that these organisms also have responded to the changes in land and water use.

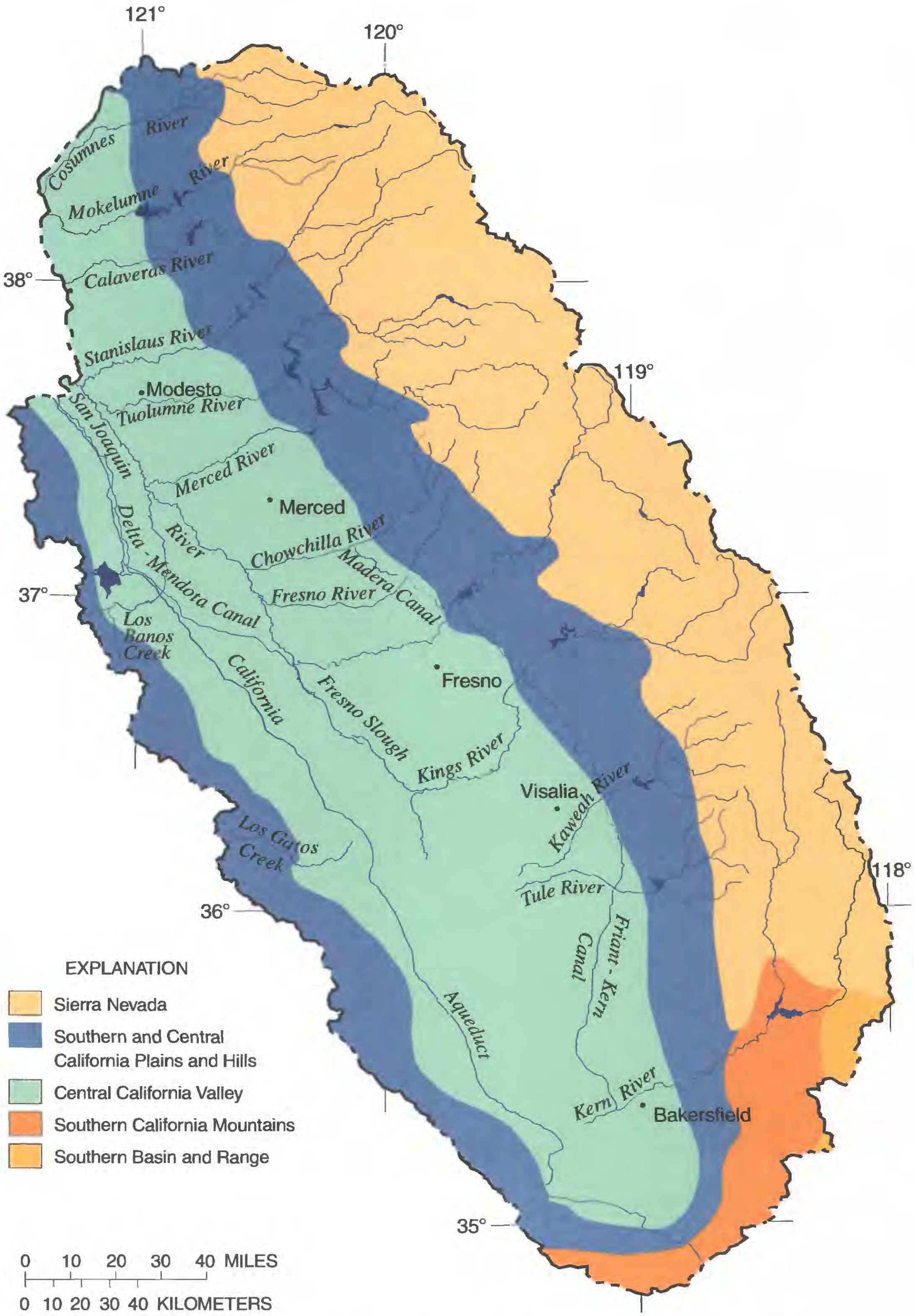

Figure 9. Ecoregions in the San Joaquin–Tulare Basins, California, study unit (from Omernik, 1987).

Table 2. Habitat characteristics of streams typically associated with fish assemblages of the San Joaquin–Tulare Basins, California, study unit

[Data from Moyle and Nichols, 1973, 1974; Moyle, 1976; Brown and Moyle, 1987; Brown, 1996. >, greater than; <, less than]

Habitat characteristics	Fish Assemblages			
	Rainbow trout	Squawfish-sucker-hardhead	Deep-bodied fish	California roach
Dominant habitat	Riffles	Deep pools	Large open channels, backwaters	Shallow pools
Common substrates	Boulder, cobble, and gravel	Boulder, cobble, gravel, and sand	Sand, mud, and silt	Cobble, gravel, sand, and silt
Altitude (feet above sea level)	>1,500	100-1,500	<100	100-1,500
Stream type	Perennial	Perennial	Perennial	Intermittent
Stream gradient	Steep	Moderate	Flat	Variable
Water velocity	Fast	Moderate	Variable	Variable
Maximum water temperature (°F)	<70	>68	77-86	>86 in some streams
Turbidity	Clear	Moderate	Turbid	Clear to moderate
Dissolved oxygen	High	Moderate	Moderate to low	Moderate to low

Surface-Water Hydrology

The San Joaquin River receives water from tributaries draining the Sierra Nevada and Coast Ranges, and except for streams discharging directly to the Sacramento–San Joaquin Delta, is the only surface-water outlet from the study unit. The water quality of the San Joaquin River is of critical interest because it flows to the delta. Both the Delta–Mendota Canal, which supplies irrigation water to farms in the western San Joaquin Valley, and the California Aqueduct, which supplies part of the drinking water for 15 million people in southern California (Metropolitan Water District of Southern California, 1990), originate in the delta.

Total mean annual runoff from the Sierra Nevada drainage to the San Joaquin Valley is 8,840,000 acre-feet per year (acre-ft/yr) (Nady and Larragueta, 1983). In contrast, most streams that drain the Coast Ranges are intermittent or ephemeral and contribute an insignificant amount of water to the valley. The total mean annual runoff from the Coast Ranges, including the Tehachapi Mountains, is estimated to be 92,600 acre-ft/yr (Nady and Larragueta, 1983). This represents about one percent of surface water entering the San Joaquin Valley from the adjacent highlands.

Distribution Systems

Farming in the San Joaquin Valley began in the early 1800s with fields irrigated by river water that was diverted through natural or hand-dug channels. This practice restricted agriculture to lands in the vicinity of major surface-water supplies (California Department of Water Resources, 1982, p. 25–27). The discovery of gold in the Sierra Nevada in January 1848 accelerated the influx of settlers (Thomas and Phoenix, 1976, p. E10) and, with this influx, the development of water resources. Reservoirs and widespread networks of ditches and flumes were built to divert water from streams at higher elevations and to sluice the gold-bearing deposits. More than 4,000 mi of mining canals and ditches were in operation by the mid-1860s (California Department of Water Resources, 1983, p. 7). After mining ceased, the ditches were used to transport water for irrigation.

Thousands of miles of canals and laterals (small, often hand-dug canals) were constructed to drain wetlands, and agricultural irrigation expanded to the valley floor. By 1900, the Kern River and much of the Kings River had been diverted by a series of canals constructed to serve lands throughout the southern San Joaquin Valley (Nady and Larragueta, 1983). By 1910, almost all of the surface-water supply in the San Joaquin Valley had been diverted (Williamson and others, 1989, p. 44).

Beginning in the late 1940s the Federal government became involved with irrigation development and was responsible for construction of substantial storage, pumpage, and conveyance facilities in California (Williamson and others, 1989, p. 45). The U.S. Bureau of Reclamation (BOR) constructed the Madera Canal to divert water north from below the Friant Dam at Millerton Reservoir and the Friant–Kern Canal to divert water south. In the 1950s and 1960s additional areas were brought into production using water from the Sacramento River and Trinity River drainage basins north of the study unit, using the

Delta–Mendota Canal (BOR) and the California Aqueduct (BOR and State of California).

Most of the major surface-water distribution systems supply water for agriculture (table 3 and fig. 10). Little municipal supply is provided by these distribution systems in the study unit. The California Aqueduct supplies agricultural areas in the southern end of the study unit and provides municipal supply to southern California. The Hetch Hetchy Aqueduct and the Mokelumne Aqueduct transport water from the San Joaquin Basin to municipal users in the San Francisco Bay region.

Major Reservoirs

The surface-water hydrology of the San Joaquin–Tulare Basins study unit has been significantly modified by development of water resources. Almost every major river entering the valley from the Sierra Nevada has one or more reservoirs. Those containing more than 75,000 acre-feet (acre-ft) of storage are shown in figure 11 and listed in table 4. The only major stream in the study unit without a major reservoir is the Cosumnes River. The construction of these reservoirs greatly modified the timing of surface-water discharge from the Sierra Nevada into the valley, primarily by retaining and delaying discharge of large amounts of snowmelt runoff.

The major purpose of each reservoir is shown in figure 11 and is given in table 4. Seventeen of these 25 reservoirs are operated at least in part for hydropower production, and 14 reservoirs are operated at least in part for irrigation. Only three of the reservoirs have any significant municipal use: Hetch Hetchy Reservoir is owned and operated by the City and County of San Francisco for water supply in the San Francisco area; Pardee Reservoir is owned and operated by East Bay Municipal Utility District for water supply in the east San Francisco Bay area; and San Luis Reservoir is jointly owned and operated by the California Department of Water Resources (DWR) and the BOR as a major storage reservoir for water from the Sacramento–San Joaquin Delta, which is exported south by the California Aqueduct and the Delta–Mendota Canal. Most of the reservoirs also provide flood control.

Annual Discharge

Average annual runoff for 1951 to 1980, shown as average depth of water over the drainage basin (Gebert and others, 1987) in inches per year, is highly variable throughout the study unit (fig. 12*A*). As with precipitation, runoff is higher in the Sierra Nevada than in the Coast Ranges. Most surface water in the study unit is snowmelt runoff from the Sierra Nevada.

Barcharts of annual stream discharge for 1950–1991 at seven representative sites are shown in figures 12*B–H*. Annual discharges vary greatly from year to year. The Sierra Nevada sites, Kern River at Kernville (12*E*), Mokelumne River near Mokelumne Hill (12*G*), and Merced River at Happy Isles Bridge near Yosemite (12*H*), are located above major reservoirs. These sites show low discharge during the

Table 3. Surface-water distribution systems in the San Joaquin–Tulare Basins, California, study unit

[Data from Kratzer and Shelton, 1998. Purpose: I, irrigation; M, municipal supply; P, hydropower production. ft^3/s, cubic feet per second; mi, mile]

Site no. (fig. 10)	Distribution system	Year completed	Capacity (ft^3/s)	Length (mi)	Purpose
A	Central California Irrigation District Main Canal	1880	1,800	71	I
B	Merced Irrigation District Main Canal	1886	2,000	21	I
C	Turlock Irrigation District Main Canal	1900	2,100	22	I
D	Modesto Irrigation District Main Canal	1904	2,000	46	I
E	South San Joaquin Irrigation District Main Canal	1913	950	32	I
F	Mokelumne Aqueduct	1929	590	90	M
G	Hetch Hetchy Aqueduct	1934	460	152	M
H	Friant–Kern Canal	1944	4,000	152	I
I	Delta–Mendota Canal	1951	4,600	116	I
J	Madera Canal	1952	1,000	36	I
K	Oakdale Irrigation District Main Canal	[1]1958	[2]525	36	I
L	California Aqueduct	1968	13,100	444	I,M,P
M	Cross Valley Canal	1975	740	20	I

[1]North Main Canal
[2]South Main Canal

Figure 10. Surface-water distribution systems in the San Joaquin–Tulare Basins, California, study unit.

recent drought years (1987–1991) and high discharge during the relatively wet period that preceded the drought (1978–1986). The San Joaquin Valley sites [San Joaquin River near Vernalis (12*B*), Merced River near Stevinson (12*C*), and Cosumnes River at Michigan Bar (12*F*)] and the Coast Ranges site [Los Gatos Creek

Figure 11. Major reservoirs in the San Joaquin–Tulare Basins, California, study unit.

above Nunez Canyon, near Coalinga (12*D*)] also show the recent drought and the preceding wet period. The San Joaquin River at Vernalis site represents the total outflow from the study unit.

Seasonal Discharge

Prior to construction of major reservoirs in the study unit, maximum river discharge was in spring or early summer and minimum discharge was in the late

Table 4. Major reservoirs in the San Joaquin–Tulare Basins, California, study unit

[Data from Kratzer and Shelton, 1998. Purpose: I, irrigation; M, municipal supply; P, hydropower production]

Site no. (fig. 11)	Reservoir	Year completed	Capacity (thousand acre-feet)	Waterway	Purpose
1	Huntington	1917	89	San Joaquin River	P
2	Hetch Hetchy	1923	360	Tuolumne River	M,P
3	Shaver	1927	135	San Joaquin River	P
4	Pardee	1929	210	Mokelumne River	M,P
5	Salt Springs	1931	139	Mokelumne River	P
6	Millerton	1947	520	San Joaquin River	I
7	Isabella	1953	570	Kern River	I
8	Edison	1954	125	San Joaquin River	P
9	Pine Flat	1954	1,000	Kings River	I
10	Lloyd	1956	268	Tuolumne River	P
11	Beardsley	1957	98	Stanislaus River	I,P
12	Wishon	1958	128	Kings River	P
13	Courtright	1958	123	Kings River	P
14	Mammoth Pool	1960	123	San Joaquin River	P
15	Success	1961	85	Tule River	I
16	Kaweah	1962	150	Kaweah River	I
17	Camanche	1963	431	Mokelumne River	I
18	New Hogan	1963	325	Calaveras River	I,P
19	San Luis	1967	2,039	California Aqueduct/Delta–Mendota Canal	I,M,P
20	McClure	1967	1,026	Merced River	I,P
21	New Don Pedro	1971	2,030	Tuolumne River	I,P
22	Eastman	1979	150	Chowchilla River	I
23	Hensley	1979	90	Fresno River	I
24	New Melones	1979	2,400	Stanislaus River	I,P
25	New Spicer Meadow	1989	184	Stanislaus River	P

summer or early autumn. Reservoirs have greatly altered seasonal discharges of the surface-water systems by retaining snowmelt and delaying runoff. The general effect has been to distribute discharge more evenly throughout the year.

Barcharts for the Sierra Nevada sites (Kern River at Kernville, Mokelumne River near Mokelumne Hill, and Merced River at Happy Isles Bridge, near Yosemite) which are located above major reservoirs, show peak discharges in May and June (figs. 13*E*, 13*G*, and 13*H*), corresponding to the period of peak snowmelt. The peak discharge for the Mokelumne River near Mokelumne Hill site builds more gradually because the watershed is at a lower elevation and receives more rain than snow relative to the other Sierra Nevada sites.

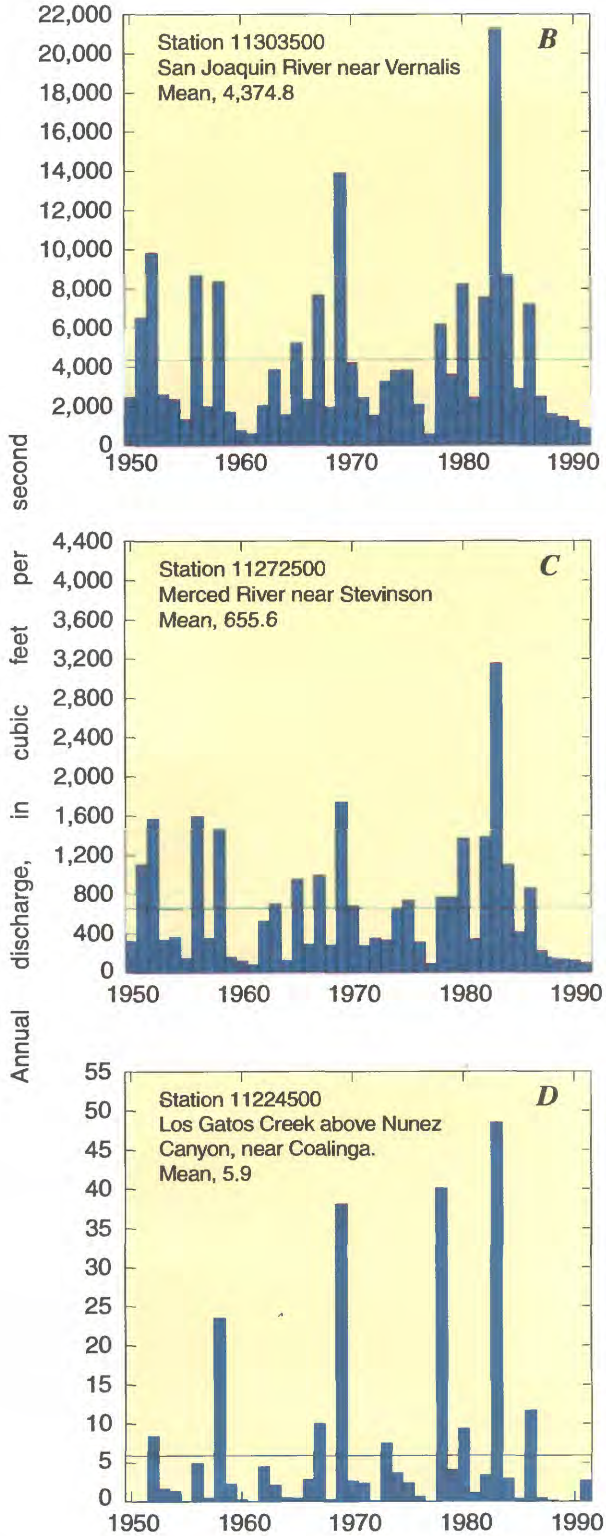

Figure 12. Spatial distribution (A) of average annual runoff, 1951–1980 (modified from Gebert and others, 1987), with barcharts (B–H) of annual discharge, 1950–1991, at selected sites in the San Joaquin–Tulare Basins, California, study unit.

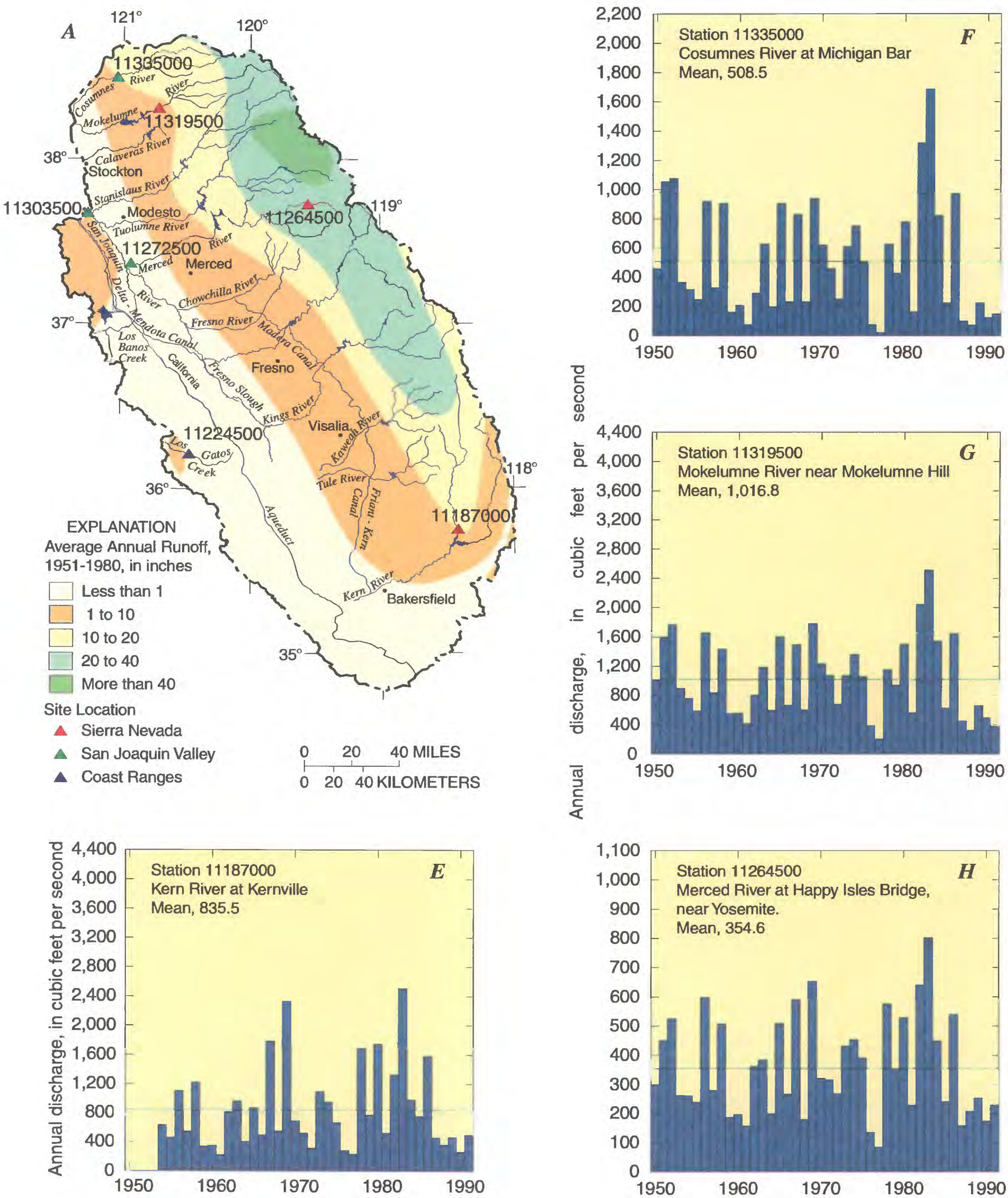

Figure 12. Continued.

At the San Joaquin River near Vernalis and Merced River near Stevinson sites, seasonal patterns are shown for both prereservoir and postreservoir-development periods (fig. 13*B* and 13*C*). The postreservoir-development period for the San Joaquin Basin (1978–1991) was a much wetter period than the prior period; thus mean monthly flows at the San Joaquin River near Vernalis site were higher for all months except June. The effect of major reservoir development on the Merced, Tuolumne, and Stanislaus Rivers can be seen in figure 13. The post-development discharges are influenced by winter rainfall (December–March), fish flow/release schedules (April–June), hydropower releases on the Merced and Tuolumne Rivers, dilution releases for delta water-quality standards on the Stanislaus River, and upstream agricultural diversions. In addition, the New Melones reservoir on the Stanislaus River is operated by the BOR in part to meet downstream water-quality standards at the San Joaquin River near Vernalis station. The postreservoir-development period for the San Joaquin River near Vernalis site (1978–1991) was a much wetter period; thus mean monthly flows were higher for all months except June.

The Cosumnes River at Michigan Bar site (fig. 13*F*) and Coast Ranges site (Los Gatos Creek above Nunez Canyon, near Coalinga, fig. 13*D*) are not affected by major upstream reservoirs. The seasonal discharge for the Coast Ranges site corresponds directly to rainfall runoff, whereas the discharge at the Cosumnes River site combines runoff with snowmelt.

Water Storage and Availability

Unimpaired flow is a term used by the DWR to represent the inflow to and discharge from a basin that would have occurred had man not altered the hydrologic system (California Department of Water Resources, 1987a). The total unimpaired flow to the valley floor in the San Joaquin Basin is computed as the sum of discharges from the San Joaquin River at Millerton Reservoir, the Merced River at McClure Reservoir, the Tuolumne River at New Don Pedro Reservoir, the Stanislaus River at New Melones Reservoir, and outflow from the Tulare Basin to the San Joaquin Basin through Fresno Slough (fig. 14*A*). Discharges from these sites provide an estimate of the total water which would be expected to reach Vernalis under natural conditions. The overall effect of reservoirs on discharges from the San Joaquin Basin is illustrated by comparing the unimpaired flow to the

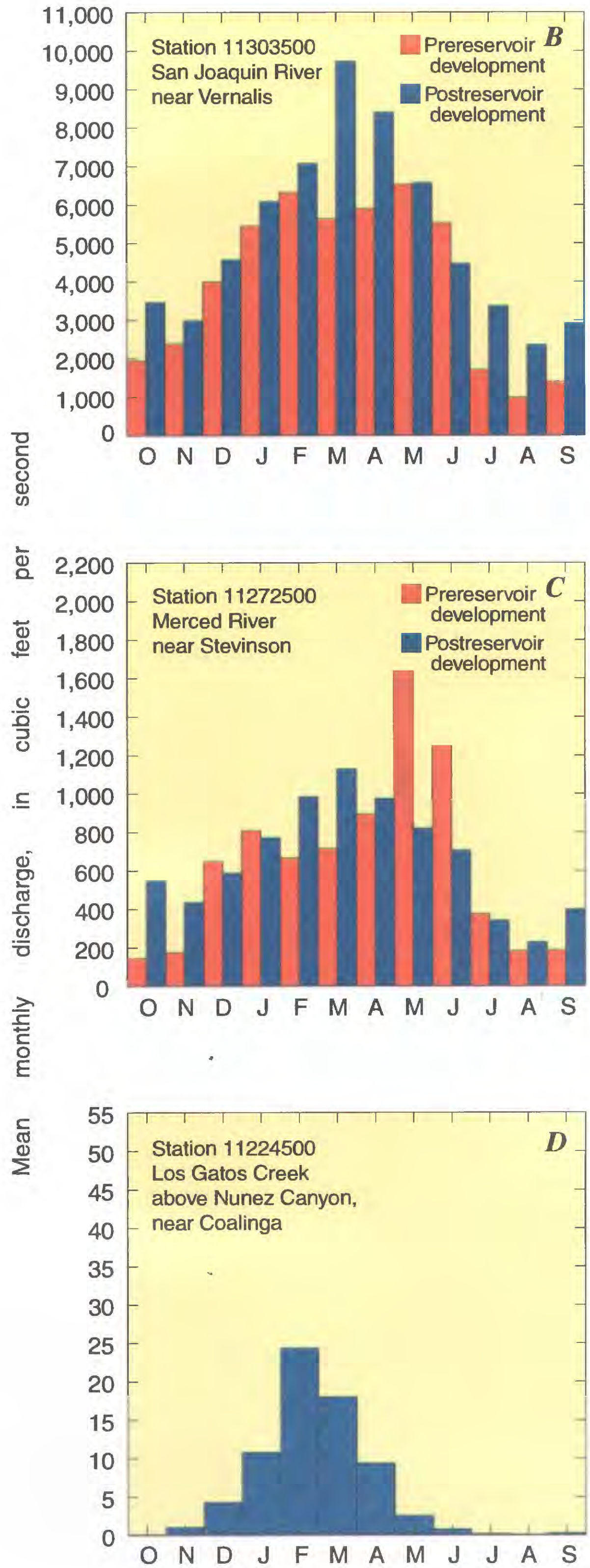

Figure 13. Location (*A*) of selected sites, with barcharts (*B–H*) of mean monthly discharge, 1950–1991, at selected sites in the San Joaquin–Tulare Basins, California, study unit.

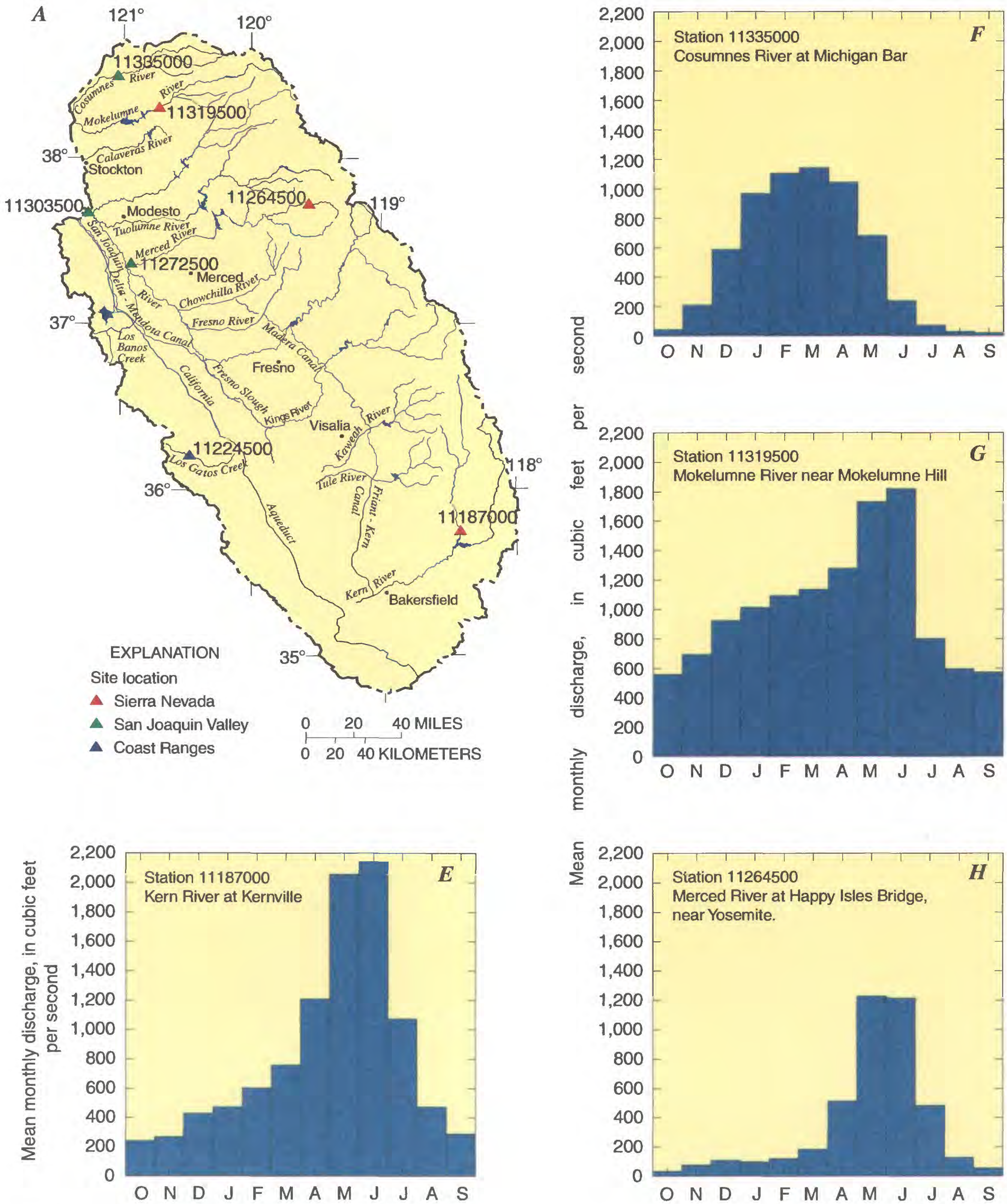

Figure 13. Continued.

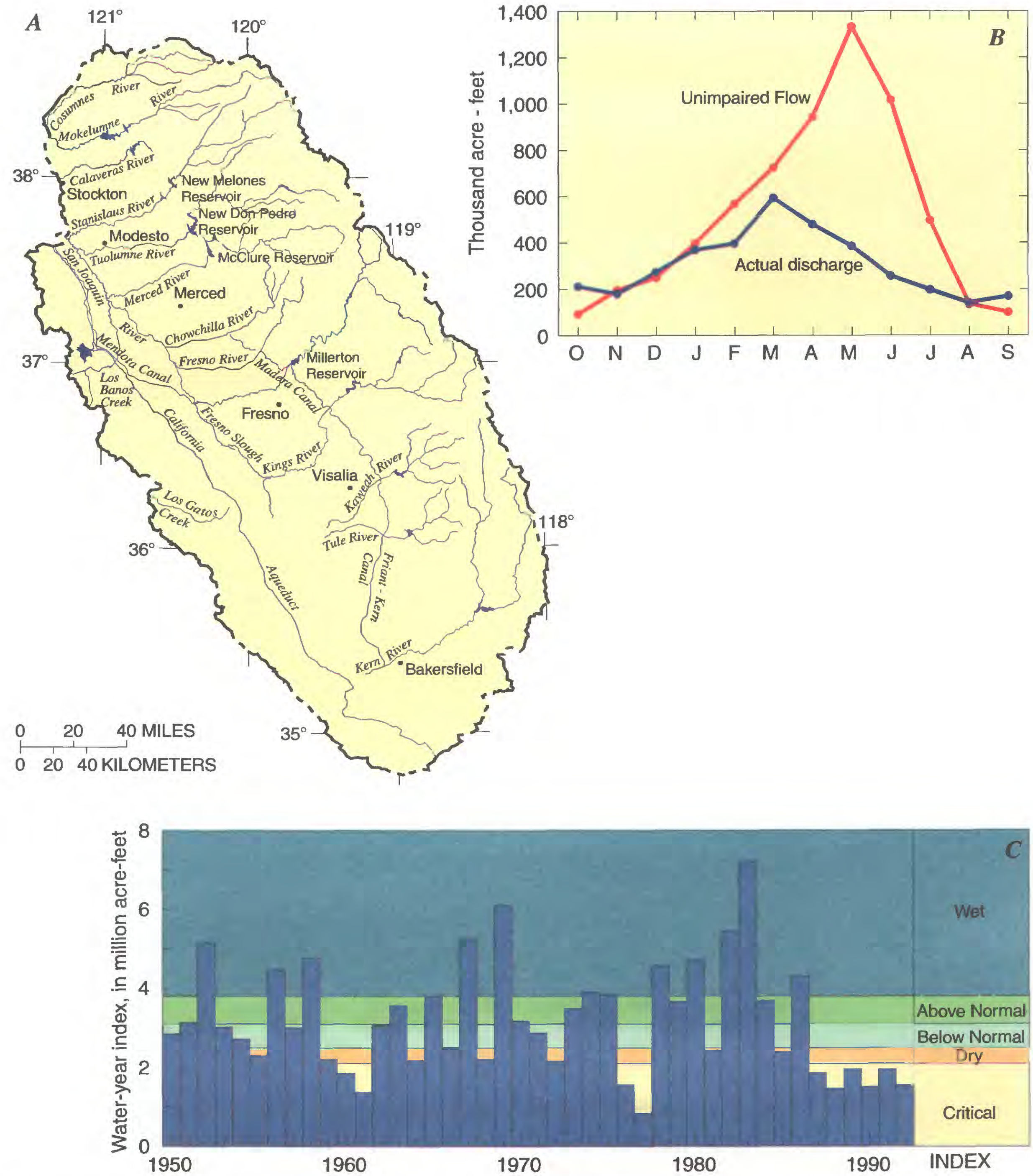

Figure 14. (A) San Joaquin–Tulare Basins, California, study unit. (*B*) Average monthly unimpaired flow to the valley floor in the San Joaquin Basin versus actual discharge from the San Joaquin Basin, California, 1979–1992 (California Department of Water Resources, 1987a). (*C*) Water-year hydrologic classifications for the San Joaquin Basin, California, 1950–1992 (California State Water Resources Control Board, 1992).

valley floor in the San Joaquin Basin to the actual discharge from the basin at Vernalis (fig. 14*B*) for the postreservoir-development period of 1979–1992. Actual discharge from the basin (about 3.7 million acre-ft/yr for 1979–1992) is approximately 60 percent of the potential natural discharge (about 6.1 million acre-ft/yr for 1979–1992). The loss of about 2.4 million acre-ft/yr is primarily due to consumptive agricultural water use (evapotranspiration) on approximately 1.44 million acres of irrigated agricultural land (California Department of Water Resources, 1994). The importing of commingled waters from the Sacramento and San Joaquin River Basins is essentially balanced by the exporting of San Joaquin River Basin water through the Friant–Kern Canal and Hetch Hetchy Aqueduct. The timing of actual discharge is more evenly distributed throughout the year, due to storage and release of water for agriculture and other uses. The four major upstream reservoirs have a combined available storage capacity of almost 6 million acre-ft. Water development and use in the basin has shifted the peak discharge from May to March and reduced it from more than 1.3 million acre-ft per month (acre-ft/mo) to about 0.6 million acre-ft/mo for 1979–1992.

Water availability in the San Joaquin Basin can be characterized by a water-year classification system used by the state of California for water allocation and regulation (fig. 14*C*). The index used for the basin is known as the 60–20–20 water-year index (California State Water Resources Control Board, 1992). Sixty percent of the forecasted unimpaired flow from April through July, 20 percent of the forecasted unimpaired flow from October through March, and 20 percent of the reservoir carryover storage from the previous water year (with a cap) are summed. Proceeding from wet to dry conditions, the water years are classified as wet, above normal, below normal, dry, or critical. The classifications for 1950–1992 are shown in figure 14*C*.

Between 1972 and 1992, there were seven wet years, three above normal, three dry, and eight critical years. Thus, it was a period of extremes. The first six years of this period were balanced; with two wet, one above normal, one dry, and two critical years. The drought of 1976–1977 was followed by a nine-year period dominated by wet years, and included five wet, two above normal, and two dry years. Following that nine-year wet period, there were six consecutive critical years, including 1991–1992.

Ground-Water Hydrology

The aquifer system of the San Joaquin–Tulare Basins study unit is contained within the southern two-thirds of the Central Valley aquifer system (fig. 15*A*). The aquifer system is made up of Post-Eocene continental rocks and deposits, which contain most of the fresh water in the valley. Pre-Tertiary and Tertiary marine sediments underlying the continental deposits contain mostly saline water, except where fresh water may have flushed out some of the saline water. The continental deposits consist primarily of lenses of gravel, sand, silt, and clay, derived from fluvial and alluvial fan sediments and interbedded with lesser amounts of lacustrine deposits. The major aquifer in the San Joaquin Valley consists of continental deposits, which are mapped on the surface by physiography, weathering characteristics, and soil type. In the subsurface, separate units are difficult to distinguish because of the difficulty of determining these characteristics on the basis of core samples and indirect methods. Therefore, the distribution of physical properties are more important than specific lithologic formation boundaries in defining the regional and local flow system (Bertoldi and others, 1991).

Abundant lenses of fine-grained deposits (clay, sandy clay, sandy silt, and silt) make up more than 50 percent of the aquifer thickness. The lenses are distributed throughout the valley, with the exception of a few areally extensive units, such as the Corcoran Clay Member (Pleistocene) of the Tulare Formation. The Corcoran Clay is part of the modified E-clay (Page, 1986) in the San Joaquin Valley. The clay is extensive and underlies an area of approximately 5,000 mi^2. This diatomaceous clay is up to 900 ft in depth and up to 160 ft in thickness beneath the Tulare Lake bed with a mean thickness of 55 ft (Davis and others, 1959; Page, 1986).

The thickness of the aquifer system, based largely on the generalized thickness of continental deposits, averages 2,400 ft and increases from north to south to a maximum thickness of more than 9,000 ft near Bakersfield. In the southeastern San Joaquin Valley, sandy marine beds underlying the continental deposits contain freshwater and are hydrologically part of the aquifer system (Bertoldi and others, 1991, p. 9).

Regional Ground-Water Flow System

The regional ground-water flow system is affected by the numerous lenses of fine-grained

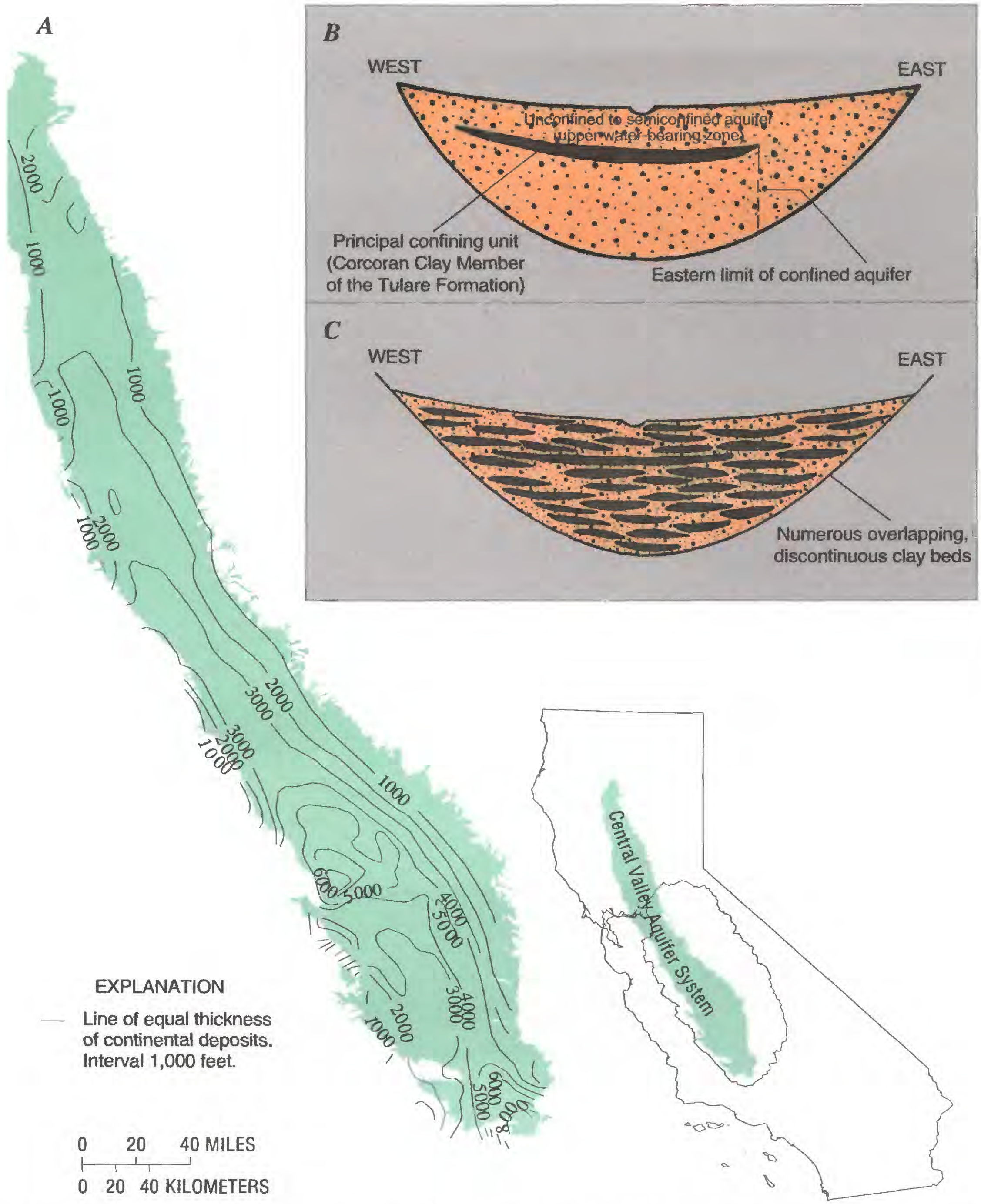

Figure 15. Central Valley, California aquifer system. (*A*) Thickness of continental deposits (adapted from Bertoldi and others, 1991). (*B*) Concept of two-layer aquifer system of the San Joaquin Valley, California (adapted from Poland and Lofgren, 1984). (*C*) Concept of single-layer aquifer system of the San Joaquin Valley, California (adapted from Williamson and others, 1989).

materials distributed throughout the aquifer. Two concepts of the aquifer system have been developed, based on the role of the fine-grained lenses on regional flow (fig. 15*B*,*C*). Poland and Lofgren (1984) define the aquifer in the San Joaquin Valley as an unconfined to semiconfined upper zone separated from a lower confined zone by the Corcoran Clay Member of the Tulare Formation (fig. 15*B*). In parts of the valley, the Corcoran Clay Member separates zones with distinctly different water chemistries (Davis and Poland, 1957; Davis and others, 1959; Davis and Coplen, 1989). Differences in hydraulic head and water chemistry above and below the Corcoran Clay support the hypothesis that the clay separates the aquifer system into unconfined or semiconfined zones (above the clay) and a confined zone (below the clay).

However, many fine-grained lenses throughout the valley have a combined thickness of several thousand feet. Also, many wells have been perforated above and below the Corcoran Clay Member, allowing flow through the well casings and gravel packs. In the vicinity of these wells, hydraulic head is equalized. In other areas where the Corcoran Clay Member is absent, head differences between shallow and deeper wells result from restriction of vertical movement by intervening clay layers (Williamson and others, 1989, p. D33–D36).

For these reasons, Williamson and others (1989) developed the concept of a single heterogeneous aquifer with varying vertical leakance and confinement (fig. 15*C*). They concluded that when the Central Valley aquifer system is examined at the regional scale, the Corcoran Clay Member is less important than the combined effect of the fine-grained lenses in controlling vertical flow. Williamson and others (1989) developed a numerical model that uses the concept of a single, mostly confined, heterogeneous aquifer system to estimate regional ground-water flow. Regardless of the role of the Corcoran Clay Member in the physical flow system, the contrasts in water chemistry above and below the clay make it an important marker in any study of ground-water quality.

Predevelopment Ground-Water Flow

Prior to development, ground water generally moved from recharge areas in the higher ground surrounding the valley floor toward lower areas in the center of the valley. Figure 16*A* depicts a hydrologic section across the valley floor, showing lateral ground-water flow roughly following the gradient of land surface from high to low elevation. Figure 16*B* is a water-table contour map; the predevelopment contours roughly correspond to land surface. Recharge was primarily from streams entering the valley from the Sierra Nevada, and to a lesser extent, directly from precipitation. Recharge through stream channels took place mostly in their upper reaches shortly after entering the valley. Most ground water was discharged as evapotranspiration in the central trough of the valley, and to a lesser extent, to streams. Potential evapotranspiration in the valley's center is about 49 in./yr, exceeding precipitation rates (Bertoldi and others, 1991, p. 17).

About 1900, flowing wells were documented along the valley trough (Mendenhall and others, 1916), indicating the upward direction of hydraulic gradients in the central part of the valley. In the Tulare Basin, most of the ground water flowed to the Tulare Lake area and evapotranspired. In the San Joaquin Basin, the Sacramento–San Joaquin Delta is the only outlet for natural discharge of surface or ground water (Bertoldi and others, 1991, p. 17). Natural recharge and discharge simulated by Williamson and others (1989) showed more recharge than discharge along the valley margins and more discharge than recharge in the low-lying central parts, corresponding to areas with flowing wells.

Ground-Water Development and Response

Ground-water development began in the Central Valley about 1880. An extensive surface-water irrigation system supplied water to the southern San Joaquin Valley, and ground water provided only a small part of the irrigation water. After 1900, well construction and ground-water withdrawal increased slowly. By 1913, annual ground-water pumpage in the Central Valley was estimated to be 360,000 acre-ft (Bertoldi and others, 1991, p. 22). Around 1930, additional ground-water development for irrigation was encouraged by the development of a deep-well turbine that pumped more efficiently from greater depths (Williamson and others, 1989). During the 1940s and 1950s, the ground-water pumpage for irrigation increased sharply (Bertoldi and others, 1991); pumpage estimates in the San Joaquin Valley were 6 million acre-ft/yr in 1948 (Williamson and others, 1989) and 7.5 million acre-ft/yr in 1952 (Davis and others, 1964). Ground-water pumpage in the Central Valley increased to an average rate of about 11.5 million acre-ft annually in the 1960s and 1970s and provided about one-half of the irrigation water. However, the proportion between surface water and ground water used for irrigation varied substantially from wet to dry years. During wet years, inexpensive surface water was used for irrigation. During dry periods, many farms used predominantly ground water. For example, during the drought of 1976–1977, ground-water pumpage in the Central Valley increased to a high of 15 million acre-ft in 1977.

Percolation of irrigation water past crop roots has replaced infiltration of intermittent stream water as

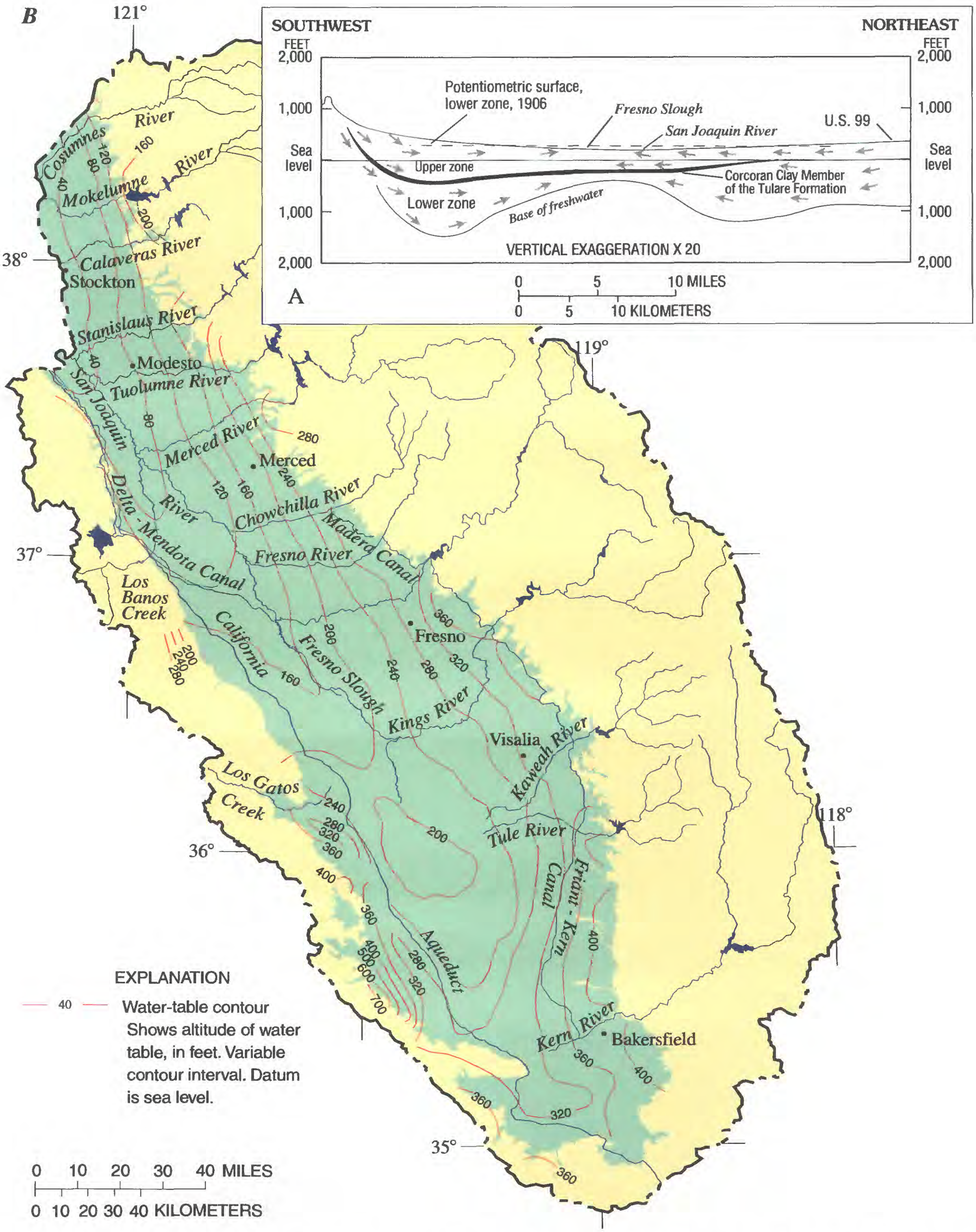

Figure 16. (*A*) Predevelopment ground-water flow in the San Joaquin Valley, California, about 1900 (Bertoldi and others, 1991). (*B*) Estimated predevelopment water table of the San Joaquin Valley, California (modified from Williamson and others, 1989).

the primary mechanism of recharge. Discharge of water through wells and evapotranspiration from crops has replaced natural evapotranspiration as the primary mechanism of discharge (Belitz and Heimes, 1990). Large withdrawals of ground water from the lower zone in the west side of the San Joaquin Valley (fig. 17*A*) caused a decline in hydraulic heads (as much as 400 ft by 1961) and a reversal of lateral ground-water flow (Bull and Miller, 1975). Water in the lower zone of the aquifer system, which previously flowed toward the center of the valley, flowed toward the pumping center on the west side of the valley in the 1950s and 1960s (fig. 17*A*). In addition, a reversal in the vertical gradient caused downward flow from the upper to the lower zone. Heavy ground-water pumpage during dry years also caused land subsidence due to sediment compaction, and more than one-half of the San Joaquin Valley is affected. Land subsidence of nearly 30 ft has been documented in some areas (Bertoldi and others, 1991, p. 32).

The water table rose in the northwestern San Joaquin Valley because of recharge from surface water irrigation. On the southern and eastern sides of the valley, the water table declined because of dependence on ground water for irrigation and the use of many shallow irrigation wells (Williamson and others, 1989, p. 63). Beginning in 1950, water was diverted through the Friant–Kern Canal from below Millerton Reservoir to the east side of the San Joaquin Valley, and water-table declines were reversed in parts of the area because pumping was reduced. In 1951, surface-water deliveries along the northwest side of the San Joaquin Valley began through the Delta–Mendota Canal and in 1967, surface water deliveries to farms along the west side and near the southern end of the San Joaquin Valley began through the California Aqueduct. The availability of imported surface water following the construction of these canals resulted in a decrease in ground-water pumpage (Belitz and Heimes, 1990). Increased surface-water delivery and decreased ground-water pumpage caused water levels to rise in both the upper and lower zones in most of these areas. Long-term water-table declines generally are less than 100 ft, except in the southern part of the San Joaquin Valley; increased irrigation recharge in some areas has caused the water table to rise as much as 40 ft (Bertoldi and others, 1991, p. 26) (fig. 17*B*).

Ground water is generally within 20 ft of land surface in the central and western areas of the valley floor (fig. 17*B*); this coincides roughly with the area of predevelopment flowing wells. The extensive use of imported surface water has resulted in a water table within 5 ft of the land surface underlying 0.8 million acres in the San Joaquin Valley (San Joaquin Valley Drainage Program, 1990b).

Because of continued heavy pumping, much of the ground-water system is still overdrafted. For example, in 1990 the net loss was 3.1 million acre-ft of ground water from storage in the San Joaquin Valley; loss of ground water from storage in 1991, the fifth consecutive year of below-normal precipitation, is projected to be about 8 million acre-ft (Carl Hauge, California Department of Water Resources, written commun., 1991).

FACTORS AFFECTING WATER QUALITY

Many factors influence the quality of ground and surface waters in the San Joaquin–Tulare Basins study unit, but the predominant factors are climate (especially the distribution of precipitation), bedrock geology and chemistry of soils derived from bedrock, and land and water use. The western part of the study unit is in the rain shadow of the Coast Ranges, and most precipitation falls on the eastern part of the study unit in the Sierra Nevada. The bedrock of the Sierra Nevada is primarily granitic. Because of the low solubility of the quartz and feldspars that make up the bulk of these rocks and soils, runoff and snowmelt from the Sierra Nevada have low concentrations of dissolved solids.

In contrast, rocks and sediments of the Coast Ranges in the western part of the study unit contain highly soluble minerals. Of particular importance are marine sedimentary formations with soluble calcium, sodium, and magnesium sulfates, and elevated concentrations of various nitrogen-containing compounds and trace elements. The precipitation in the Coast Ranges dissolves these constituents, and the resulting runoff has elevated concentrations of dissolved solids and other contaminants. Water quality may be further degraded by evaporative concentration because of the semiarid to arid climate. Runoff from the Coast Ranges is sparse, however; most of the surface water entering the hydrologic system in the study unit is from the Sierra Nevada and, therefore, generally low in dissolved solids.

Surface water in the Sierra Nevada can be degraded by land-use practices such as mining and logging. Mining can contribute dissolved solids,

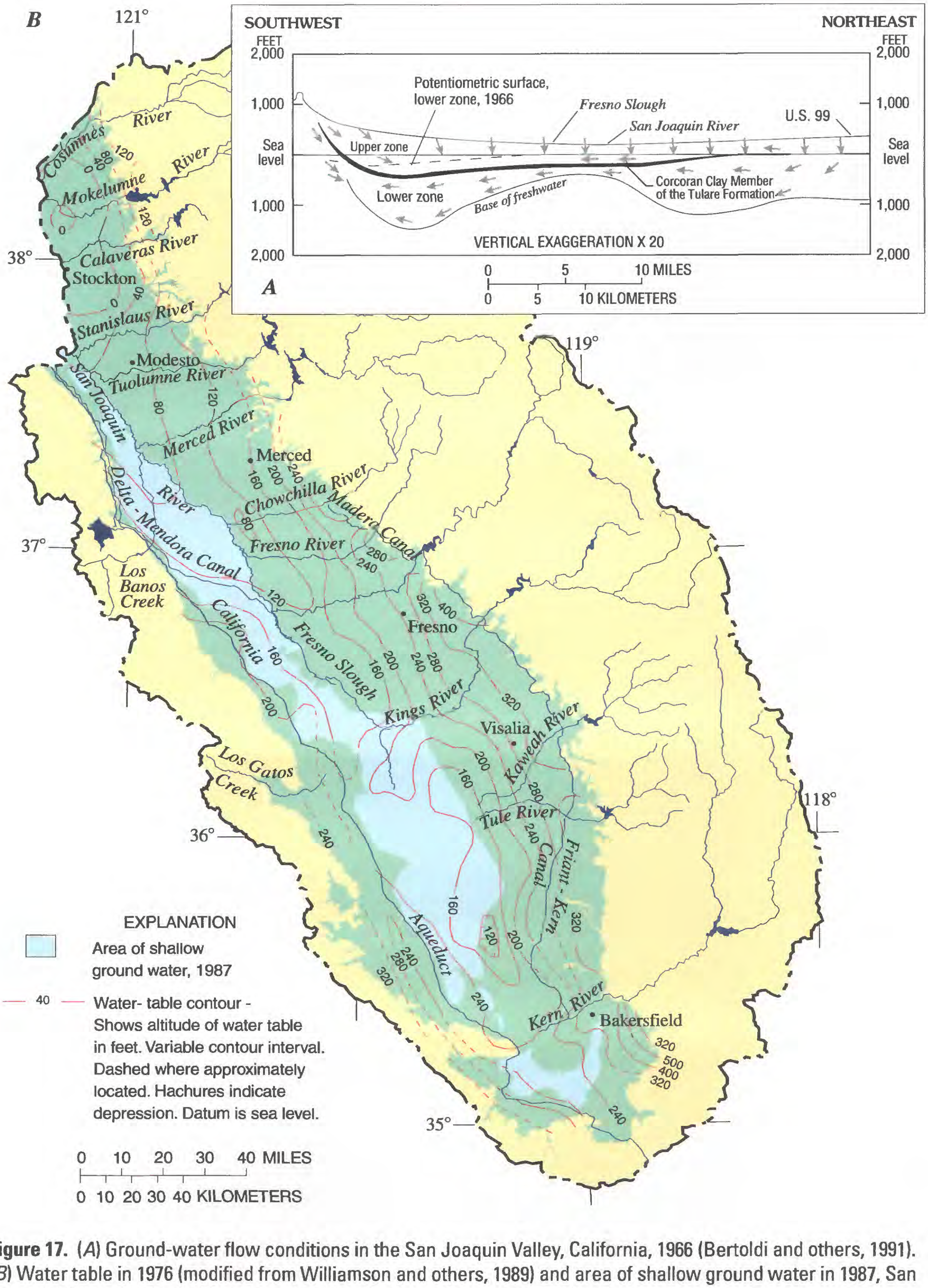

Figure 17. (*A*) Ground-water flow conditions in the San Joaquin Valley, California, 1966 (Bertoldi and others, 1991). (*B*) Water table in 1976 (modified from Williamson and others, 1989) and area of shallow ground water in 1987, San Joaquin Valley, California (San Joaquin Valley Drainage Program, 1990b).

metals, and sediment to streams; logging can result in leaching of nutrients and increased sediment loads to streams. At present, runoff from the Sierra Nevada is low in dissolved solids until the water enters the San Joaquin Valley. Surface water imported to parts of the western and southern San Joaquin Valley also is generally low in dissolved solids; however, the concentration of dissolved solids in imported water is affected by hydrodynamic factors in the Sacramento–San Joaquin Delta.

Agricultural water use is the largest nonpoint-source of water-quality degradation in the San Joaquin Valley. Irrigation has become the major source of recharge to the ground-water system, and can contain elevated concentrations of dissolved solids, nutrients, pesticides, and in some areas, trace elements. Surface water in the valley may be similarly impacted by direct runoff from irrigated areas (tailwater), by discharge of water from subsurface drainage systems that have been installed to control the level of the water table, and by discharge of poor-quality ground-water through river beds.

In addition to the effects of nonpoint agricultural sources, water quality in the valley is affected by the activities of the 2.7 million people who live in the San Joaquin–Tulare Basin study unit. Nonpoint sources of pathogens and nutrients from household septic systems degrade ground and surface waters. The effects of cities include point source discharge to rivers of nutrient-rich effluent from sewage treatment plants and stormwater runoff with elevated concentrations of metals. Volatile and other man-made organic compounds also can be introduced to both ground and surface water.

An additional factor in ground-water quality is the oxidation-reduction (redox) environment in the aquifers. The aquifers underlying the alluvial fans in the valley are largely oxidizing environments, whereas aquifers underlying the basin and lake deposit areas near the axis of the valley are reducing environments. In an aquifer the redox environment strongly influences the mobility of some trace elements and nitrate, and the potential for degradation of redox-sensitive constituents, such as some organic compounds.

Land Use

Land use was interpreted from high-altitude aerial photography in 1973–1979 using Anderson level II classifications (Anderson and others, 1976) and stored in the Geographic Information Retrieval and Analysis System (GIRAS) (U.S. Geological Survey, 1986). Approximately 39 percent of the study unit was covered by forest, 32 percent was agricultural land (25 percent cropland and pasture, 6 percent orchards and vineyards, 1 percent other agricultural land use), 23 percent was rangeland, 3 percent was barren land, water, tundra, and perennial snow or ice, 2 percent was urban, and less than 1 percent was Wetland (fig. 18). The forested land is predominantly in the Sierra Nevada, and rangeland is predominantly in the foothills of the Sierra Nevada and the Coast Ranges. Urban areas and agricultural land are predominantly on the valley floor; most orchards and vineyards are on the east side of the valley. Although these data are suitable for representing regional spatial patterns of land use, there are discrepancies in interpretation across quadrangle boundaries, such as at 38 degrees latitude, which may be caused by inconsistent interpretation. For example, north of the 38 degree latitude line, rangeland has shifted to agricultural land and forest land has shifted to rangeland.

Agricultural Land Use

Most of the valley floor is agricultural land. In 1987, about 10.5 million acres in the San Joaquin Valley was farmland (San Joaquin Valley Drainage Program, 1990b, p. 50). Abundant water combined with the long growing season results in an exceptionally productive agricultural economy in the San Joaquin Valley. In 1987, approximately 10 percent of the total value of agricultural production in the United States came from California, of which 49 percent, or $6.82 billion, was generated in the San Joaquin Valley. Major products include livestock and livestock products (35 percent), fruit and nuts (33 percent), cotton (13 percent), vegetables (6.5 percent), hay and grains (6 percent), and other crops (6.5 percent).

Although the GIRAS data are sufficient for describing the general land use and distribution, detail is lacking in specific crop types. The DWR's Division of Planning, Statewide Planning Branch, Land and Water Use prepares detailed maps of the agricultural land use on the valley floor every 6–7 years. Figure 19 shows the DWR 1987 land-use data for Madera County. The distribution of crops generally reflects the distribution of soil texture and chemistry. About 43 percent of the irrigated land on the west side of the valley is planted in cotton, which is a salt tolerant crop.

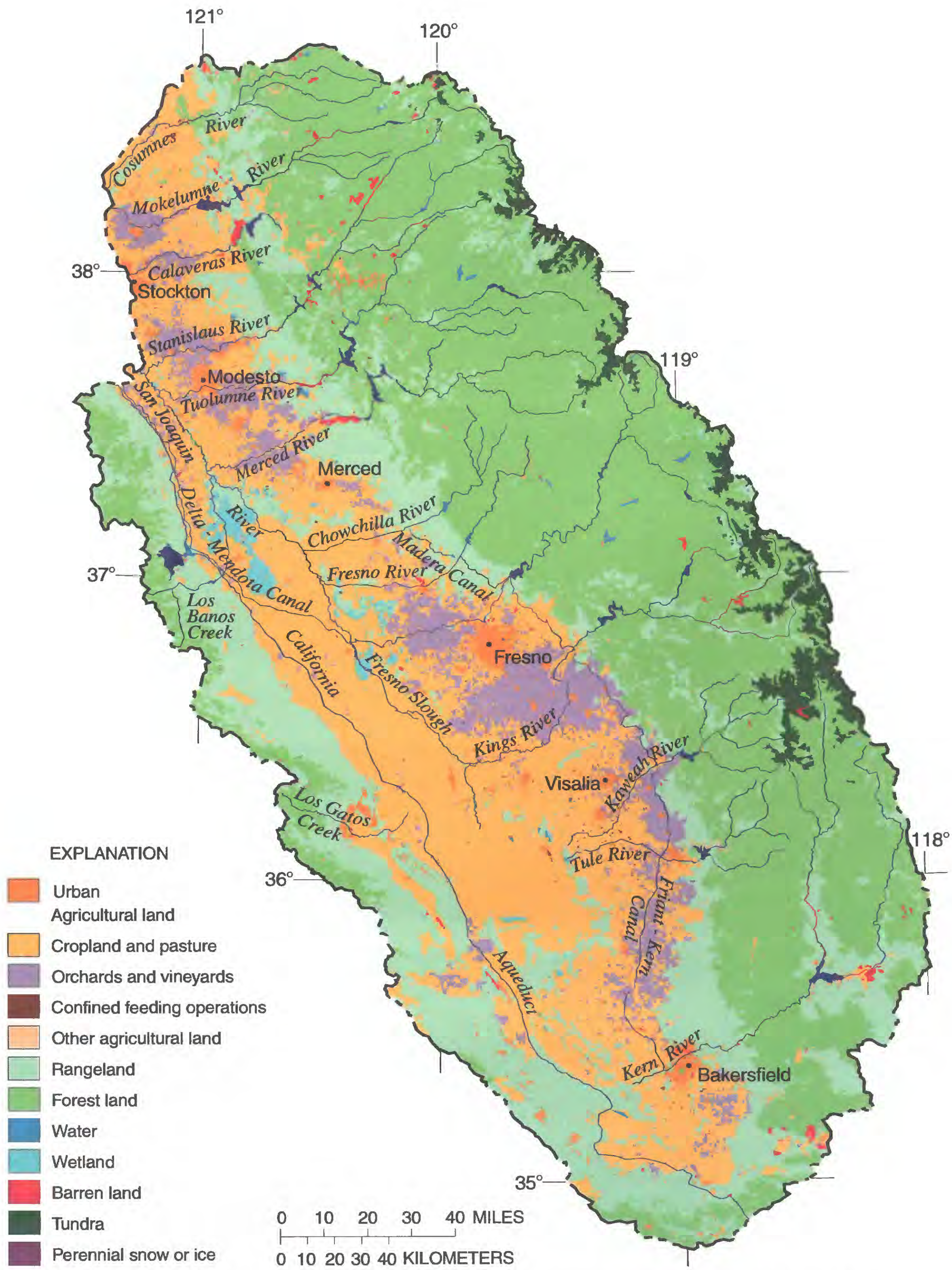

Figure 18. Distribution of major land-use classifications, San Joaquin–Tulare Basins, California, study unit (U.S. Geological Survey, 1986).

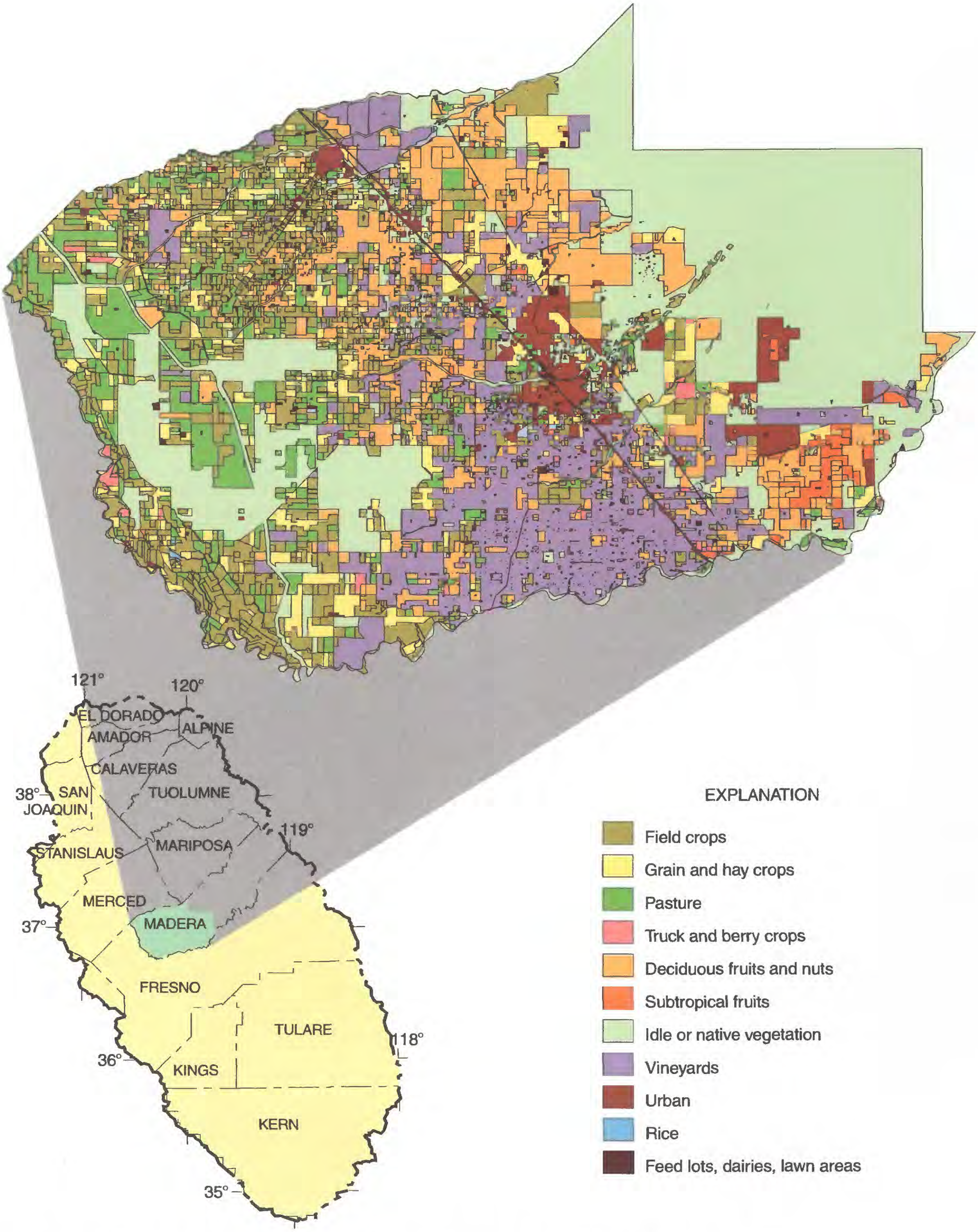

Figure 19. Distribution of agricultural land use, valley floor part of Madera County, California, 1987.

In contrast, 31 percent of the crop land on the east side is planted in fruit and nut trees, which are intolerant of salinity and some trace elements, accounting for about 92 percent of the total acreage of these crops in the valley.

The importance of agriculture to the economy of California is clear from employment statistics. Statewide in 1987, agriculture-related employment accounted for at least 17.3 percent of employment and 18.5 percent of total payroll. Within the San Joaquin Valley, these categories were 48.6 and 54.2 percent, respectively. In 1987, agriculture-related employment accounted for more than 50 percent of employment in Kings, Madera, Merced, and Stanislaus counties, and about 50 percent in Fresno, San Joaquin, and Tulare counties. In Kern County, agriculture accounted for only 20 percent of employment, reflecting the development and growing importance of other industries, such as petroleum (San Joaquin Valley Drainage Program, 1990b).

Urban Land Use

Population in the San Joaquin–Tulare Basins study unit is estimated at 2,719,958 from the 1990 Census (U.S. Department of Commerce, 1990). About 46 percent of the population in the study unit is in the major urban areas of Fresno (453,388), Bakersfield (302,605), Stockton (262,046), and Modesto (230,609) (California Department of Finance, 1991) (fig. 20). Most of the remaining population is in small farming communities in the San Joaquin Valley. The Sierra Nevada and Coast Ranges adjacent to the valley are sparsely populated.

The California Department of Conservation (1988, 1992) has documented a small shift in land-use type from agricultural to urban. Nine counties (Amador, El Dorado, Fresno, Kings, Madera, Mariposa, Merced, Sacramento and Stanislaus), which are fully or partially in the study unit, were surveyed in 1988 and 1990. For these counties, 11,646 acres of agricultural land use (farmland and grazing) directly converted to urban land use between 1988 and 1990; 8 acres of urban land use converted to agricultural land use. Other counties in the study unit were only partially surveyed during this period and were not included in the converted acreage.

Water Use

California has the largest offstream water use in the nation, and consistently leads all states in surface and ground-water withdrawals (Templin, 1990, p. 173). Total water use in the study unit in 1990 was about 30.2 million acre-ft (W.E. Templin, U.S. Geological Survey, written commun., 1992). Hydropower production, the only instream water use studied under the USGS water-use program, accounted for 14.1 million acre-ft. Total offstream water use in the study unit was 16.1 million acre-ft, of which 91 percent was for irrigated agriculture.

Overall consumptive use of water in the study unit was about 12.1 million acre-ft. About 58 percent of this use was supplied with surface water and 42 percent with ground water. Of the surface-water use, about 38 percent (2.7 million acre-ft) was imported from the Sacramento–San Joaquin Delta through the California Aqueduct (State Water Project) and the Delta–Mendota Canal (Central Valley Project). About 22 percent of total consumptive use was supplied with imported water (California Department of Water Resources, 1994; U.S. Bureau of Reclamation, 1990). Of this consumptive water use, 94.9 percent was for irrigated agriculture in 1990. Domestic use (for example, drinking water) accounted for only 1.1 percent of the consumptive use in the study unit; virtually all of this was ground water. Figure 21 shows the distribution of total offstream water use and relative amounts supplied by ground water and surface water in 1990. The U.S. Geological Survey uses hydrologic units (fig. 21) to manage the National Water Data Network (U.S. Geological Survey, 1978).

Point Sources

Point-source discharges to surface waters in the study unit are identified and quantified through National Pollutant Discharge Elimination System (NPDES) permit records kept with the State regulatory agencies. Excluding hydropower facilities and fish hatcheries, there are 32 point-source discharges in the study unit; average discharge rates are more than 0.5 ft^3/s (fig. 22). Of these 32 point sources, 18 are wastewater treatment plants, 7 are food processing facilities, 3 are manufacturing facilities, 3 are oil or gas production facilities, and 1 is a sand- and gravel-mining facility. Five of the point sources have average discharges greater than 10 ft^3/s. These include the wastewater treatment plants for the cities of Merced,

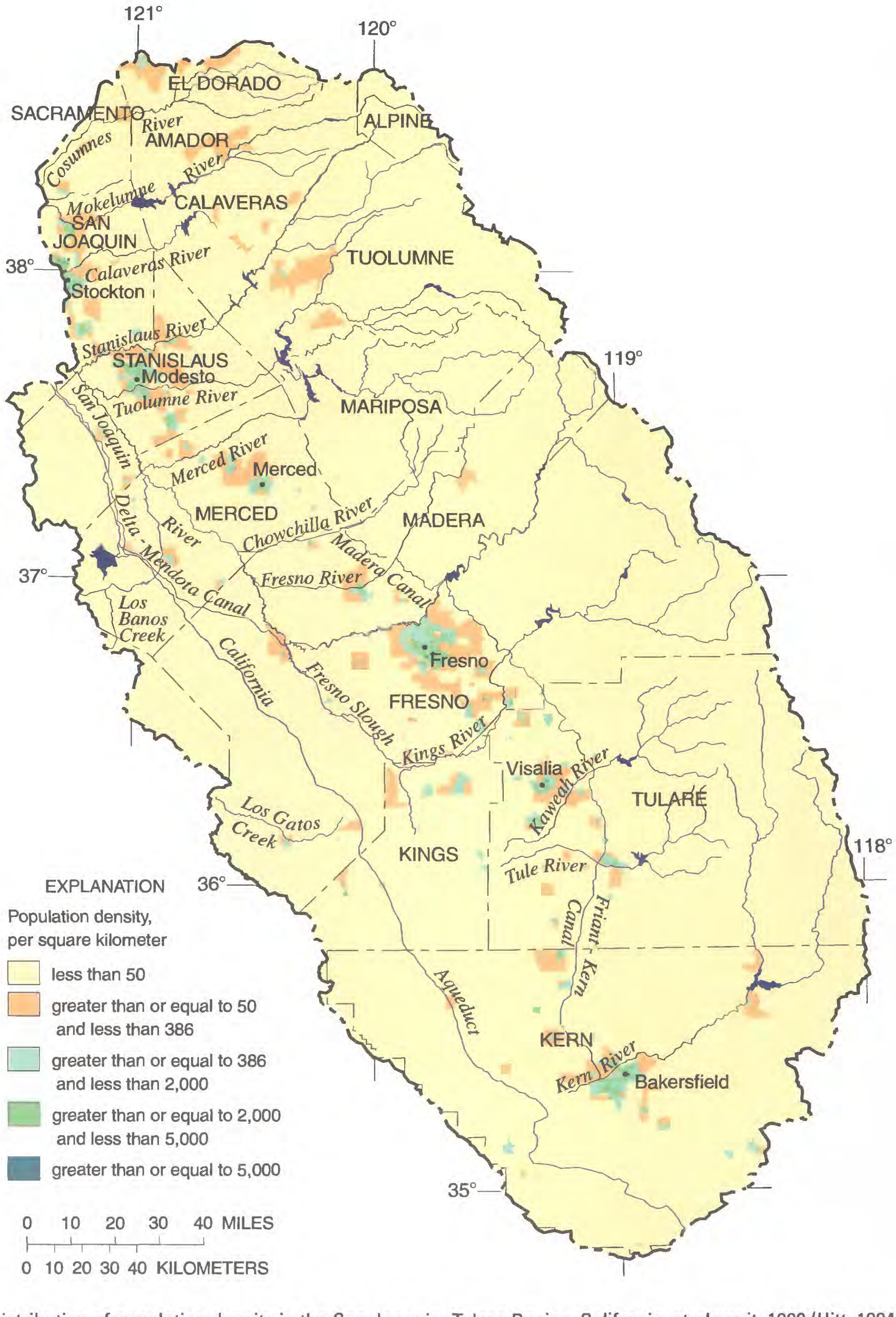

Figure 20. Distribution of population density in the San Joaquin–Tulare Basins, California, study unit, 1990 (Hitt, 1994).

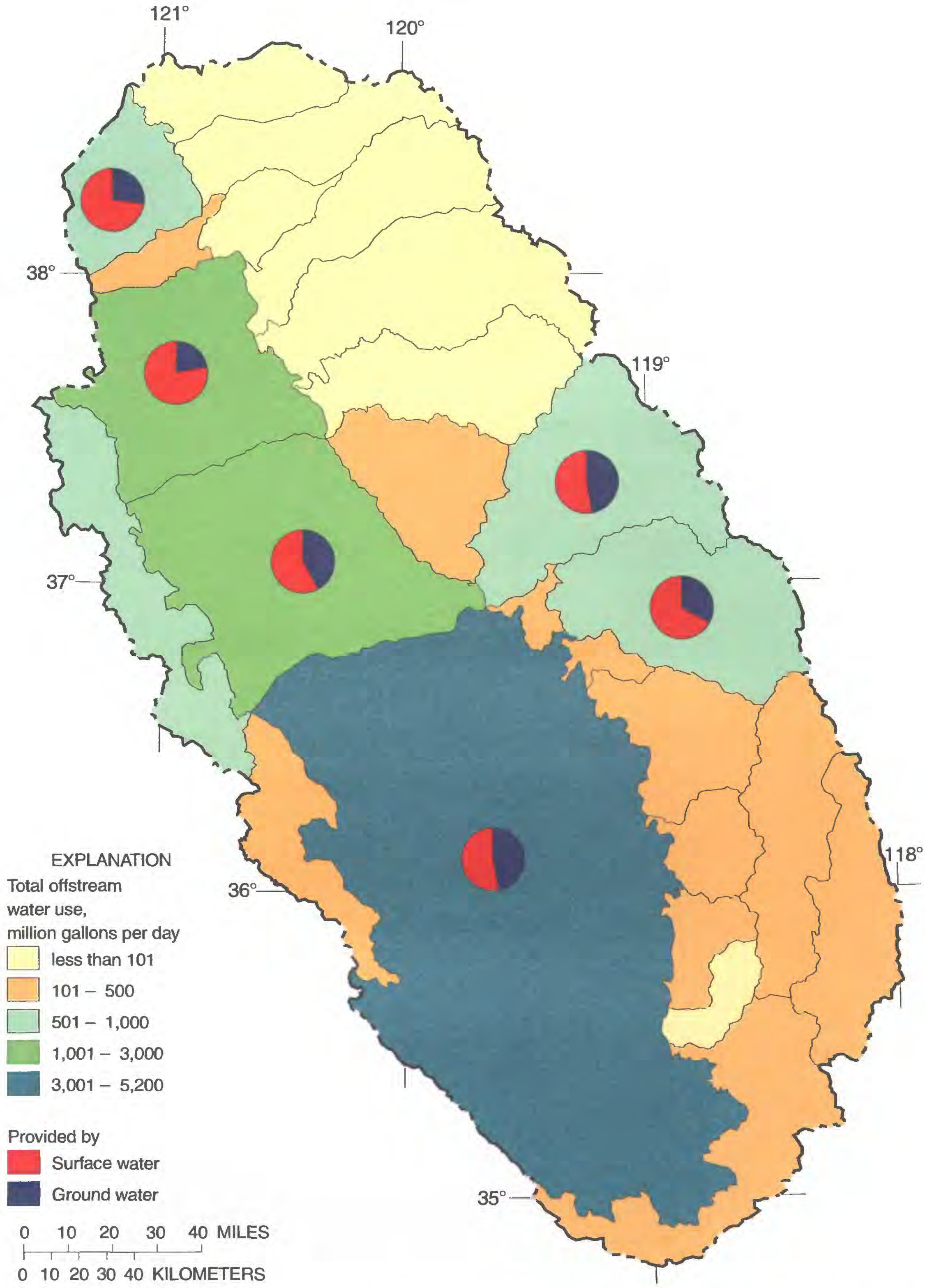

Figure 21. Total offstream water use by hydrologic unit and percentages of ground water and surface water in the San Joaquin–Tulare Basins, California, study unit, 1990.

Figure 22. Location of National Pollutant Discharge Elimination System point sources with discharges greater than 0.5 cubic feet per second in the San Joaquin–Tulare Basins, California, study unit.

Modesto, Turlock, and Visalia, and the oil and gas production facility of Texaco Oil near Bakersfield. The largest cities in the study unit, Fresno and Bakersfield, discharge to percolation ponds with land treatment and do not have NPDES permits for discharging to surface waters. The third largest city in the study unit, Stockton, discharges to the San Joaquin River outside of the study unit in the Sacramento–San Joaquin Delta. Modesto discharges to the San Joaquin River only in the winter; the wastewater is held in percolation ponds and applied to land during the rest of the year. The Turlock and Merced wastewater-treatment plants discharge to the San Joaquin River through Turlock Irrigation District drain lateral Number 5 and Owens Creek, respectively. The Visalia and Texaco Oil discharges are in the Tulare Basin (Kaweah and Kern Rivers, respectively).

Agricultural Sources

Discharges to the San Joaquin River

The water quality of the San Joaquin River is affected by the discharge of excess irrigation water that leaves a field without infiltrating the soil (tailwater or surface drainage water) and shallow ground water that infiltrated the soil past the crop root zone and is collected by tile drains (subsurface drainage water). Tile drains are used in areas of shallow ground water to lower the water table below the root zone to allow continued cultivation. There are approximately 58,000 acres of tile drains in the lower San Joaquin River basin. Subsurface water collected by tile drains often has high concentrations of salts including trace elements such as selenium and nitrate. Pesticides rarely are detected in west side, subsurface drainage water, but have been found in tailwater (Gilliom and Clifton, 1990).

Figure 23 shows 104 discharge points to the perennial San Joaquin River (California Regional Water Quality Control Board, 1989; Kratzer and others, 1987). Of the discharge points shown, 87 are surface drainage only, 3 are subsurface tile drainage only, and 14 are a combination of surface and subsurface drainage. There are five discharge points with irrigation-season flows averaging greater than 25 ft^3/s. These are (from north to south): Hospital and Ingram Creeks, Spanish Grant Drain, Orestimba Creek, Mud Slough, and Salt Slough. Except for Orestimba Creek, which is entirely surface drainage, these discharge points are a combination of surface and subsurface drainage. During summer low-flow periods, these agricultural discharge points can account for most of the flow of the San Joaquin River. The year-round effect of surface and subsurface drainage from agricultural sources is a major water-quality concern.

Pesticides

Large quantities of agricultural chemicals are used in California. Based on the Census of Agriculture (U.S. Department of Commerce, 1987) crop data and estimates of application rates, California ranked 10th in herbicide use in the conterminous 48 states (Gianessi and Puffer, 1991), first in fungicide use (Gianessi and Puffer, 1992a), and first in insecticide use (Gianessi and Puffer, 1992b). California accounted for roughly 16 percent of the total pesticide use. In 1991, the annual total pesticide use on crops in California was 161.1 million pounds active ingredient (lb a.i.) (California Department of Pesticide Regulation, 1991a,b). Pesticide application in the San Joaquin–Tulare Basins was approximately 88.3 million lb a.i., approximately 55 percent of California's total and roughly 9 percent of the pesticide used in the conterminous United States. Application on the valley floor, 88.0 million lb a.i., accounts for nearly all application in the study unit.

California's pesticide data base is maintained by the California Department of Pesticide Regulation. Prior to 1990, the State of California required reporting all applications of restricted-use pesticides and all pesticides applied by licensed pesticide applicators. Applications of nonrestricted-use pesticides by private farming operations were not reported. Since 1990, all pesticide applications must be reported to the California Department of Pesticide Regulation. The 1990 data base contains 1,760 pesticide codes and 2,466 commodity codes. The large variety of pesticides used reflects the diverse agricultural practices of the San Joaquin Valley, as well as the use of pesticides for various purposes throughout the year. Table 5 lists the 20 most heavily applied pesticides, which accounts for approximately 79 percent (by weight) of the total pesticides used in the San Joaquin Valley. The large number of commodity codes indicates the large variety of agricultural and nonagricultural uses. However, the 20 crops listed in table 6 account for 87 percent (by weight) of the pesticides used in the San Joaquin Valley.

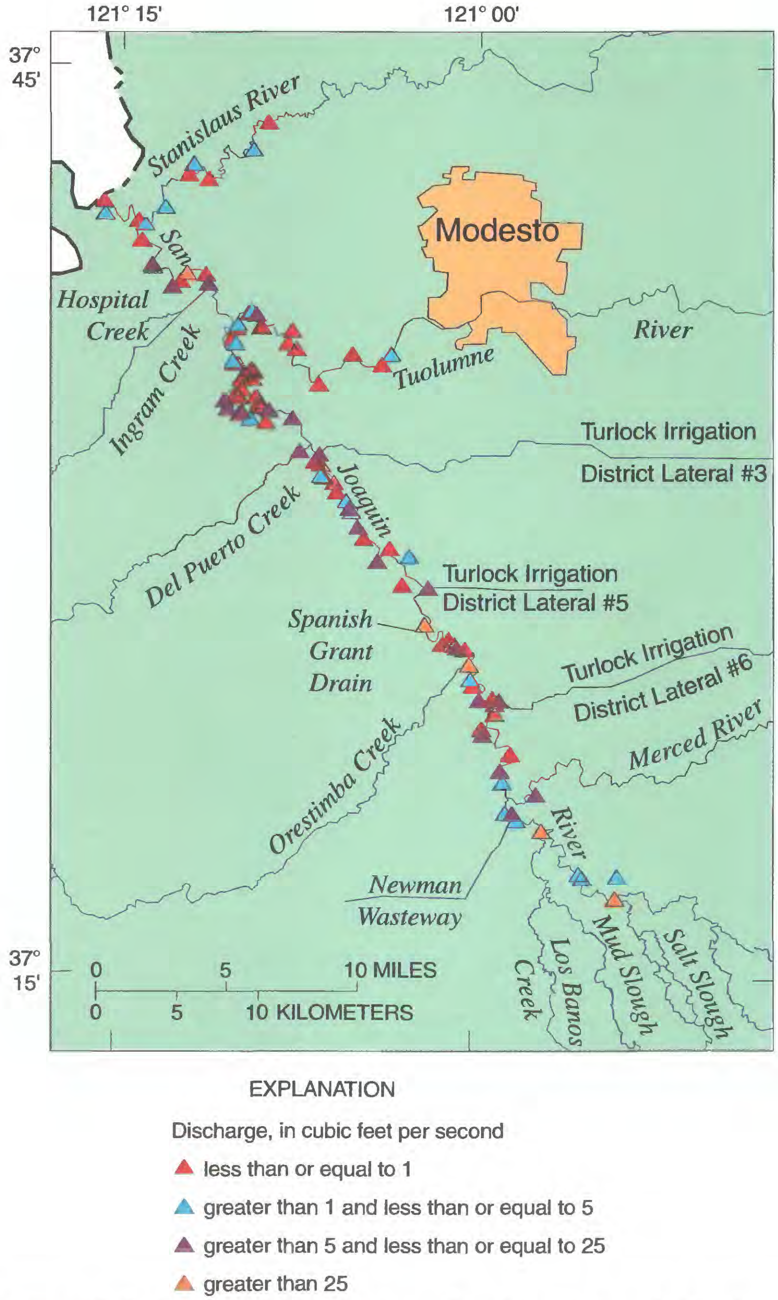

Figure 23. Agricultural discharges, lower San Joaquin River, California.

Nutrients from Fertilizers

Agriculture in the study unit depends on large applications of fertilizer. There is no data base on actual use of fertilizers in the state of California (Steven Wong, California Department of Food and Agriculture, oral commun., 1991), but fertilizer sales information has been used to estimate county-level fertilizer use for 1945 through 1985 (Alexander and Smith, 1990), and for 1985 through 1990, (U.S. Environmental Protection Agency, 1990). Generally, nitrogen and phosphorus fertilizer sales increased from 1965 to 1980 and decreased in 1985 and 1990 (fig. 24*A*). This corresponds to the overall acreage in production in the study unit during this time period (California Department of Water Resources, 1987b). In 1990, estimated total nitrogen and phosphorous use for the study unit was about 597 million lb a.i. In 1990, Fresno, Kern, and Tulare Counties ranked first, second, and third respectively, for total nitrogen use among counties, nationally. For phosphorus, these counties ranked first, second, and fourth. It must be

Table 5. Summary of the 20 most heavily applied pesticides in the San Joaquin Valley, California, 1991

[Data from California Department of Pesticide Regulation, 1991b]

Pesticide	Amount of active ingredient applied (x 1,000 pounds)
Sulfur	32,033
Petroleum oil, unclassified	9,970
Methyl bromide	7,282
Cryolite	2,484
Sodium chlorate	2,463
Metam-sodium	2,394
Copper hydroxide	1,991
Petroleum distillates	1,695
Glyphosate, isopropylamine salt	1,445
Ziram	1,359
Propargite	1,248
Calcium hydroxide	1,003
Trifluralin	851
Chlorpyrifos	843
Ethephon	775
s,s,s-Tributyl phosphorotrithioate	774
Diuron	638
Copper sulfate	624
Simazine	527
Parathion	511

Table 6. Amount of pesticides applied to various crops in the San Joaquin Valley, California, 1991

[Data from California Department of Pesticide Regulation, 1991b]

Crop	Amount of active ingredient applied (x 1,000 pounds)
Grapes	29,259
Almonds	11,299
Cotton	9,881
Tomatoes	3,916
Peaches	3,525
Oranges	3,278
Sugar beets	2,855
Nectarines	2,372
Plums	1,892
Carrots	1,840
Alfalfa	1,564
Walnuts	1,094
Potatoes	901
Pistachios	747
Corn	487
Beans	415
Strawberries	311
Onions	300
Sweet potatoes	229
Wheat	159

kept in mind that counties in the western United States are larger than counties in the eastern United States.

Fertilizer application per acre in 1990 (fig. 24*B*) was calculated from the county-level fertilizer estimates (U.S. Environmental Protection Agency, 1990). All fertilizer use is assumed to have been within the valley portion of the counties. Although only an estimate, this shows the great variability in fertilizer application rates within the valley.

Nutrients from Manure

Another source of nutrients is livestock manure. R.E. Alexander (U.S. Geological survey, written commun., 1992) used two sources of data to estimate county-level nitrogen and phosphorus content in manure: 1987 Census of Agriculture (U.S. Department of Commerce, 1987 [for animal populations]) and the U.S. Soil Conservation Service (1992) Agricultural Waste Management Field Handbook (for nutrient content by each animal type). These animals included cows, calves, hogs, sheep, horses, and poultry. In 1987, an estimated 318 million lb a.i. of nitrogen and phosphorus from manure was generated in the study unit. County-level estimates, assuming all manure is generated on the valley floor portion of the counties, show high concentrations of manure nutrients in San Joaquin, Stanislaus, Merced and Tulare counties (fig. 25*A*). The proportion of phosphorus to total nutrients from manure varies for each animal; county averages of phosphorus to total nutrients range from 14 to 22 percent.

About 38 percent of the manure in the study unit comes from milk cows. Figure 25*B* shows a large concentration of dairies in Stanislaus, Merced, Kings, and Tulare Counties (R. Schnagel, California Regional Water Quality Control Board, written commun., 1992); these counties show the highest manure nutrient rates in the study unit. Waste-discharge regulations generally allow discharges to surface waters from dairies only during large storms. The Regional Board has identified several waterways believed to have received dairy waste (California Regional Water Quality Control Board, 1989; California State Water Resources Control Board, 1990, 1991). However, these discharges are

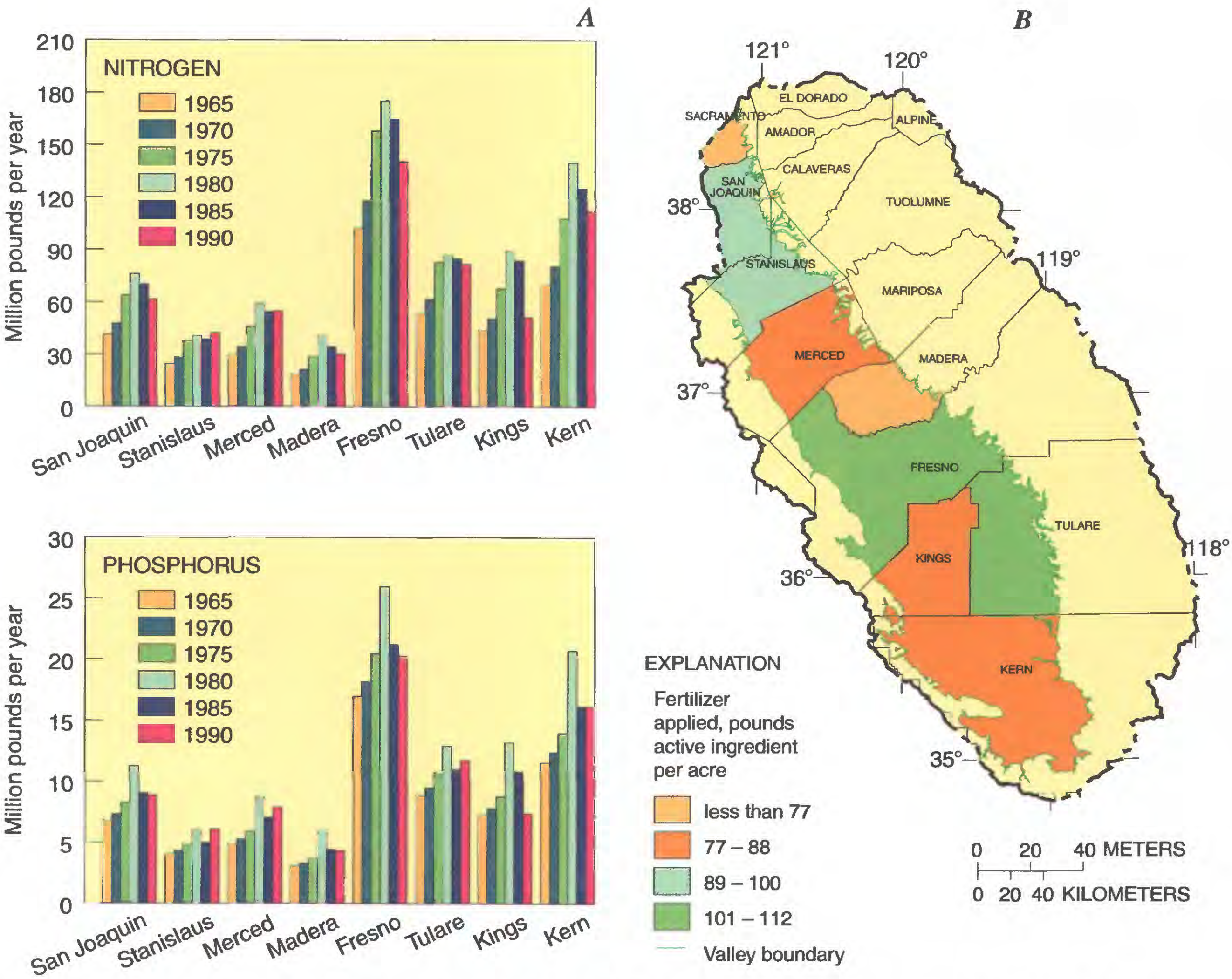

Figure 24. Estimated fertilizer applications in the San Joaquin Valley, California. *(A)* Nitrogen and phosphorus fertilizer application by county, 1965–1990. *(B)* Total per acre on valley floor by county, 1990.

unauthorized, and no data are available to quantify their magnitude.

MAJOR WATER-QUALITY ISSUES

The San Joaquin–Tulare Basins NAWQA study focuses on the quality of ground- and surface-water resources in the San Joaquin Valley, the area with most of the population, agriculture, and water use. Information for the Sierra Nevada will be used primarily to establish background water-quality conditions. The major water-quality issues of concern in the San Joaquin–Tulare Basins study unit are:

Increased salinity in the lower San Joaquin River—Considered by most agencies to be the most serious water-quality issue in the study unit, the increase is attributed to a decrease in the volume of low-salinity runoff from the Sierra Nevada entering the San Joaquin River and to an increase in the volume of saline water from agricultural areas.

Elevated concentrations of naturally occurring trace elements—Primary concerns are arsenic, boron, molybdenum, uranium, and vanadium in shallow ground water in the Tulare Basin; chromium, boron, molybdenum, selenium, uranium, and vanadium in the San Joaquin River; and accumulation of trace elements including selenium and mercury in waterfowl and aquatic organisms. The distribution of and

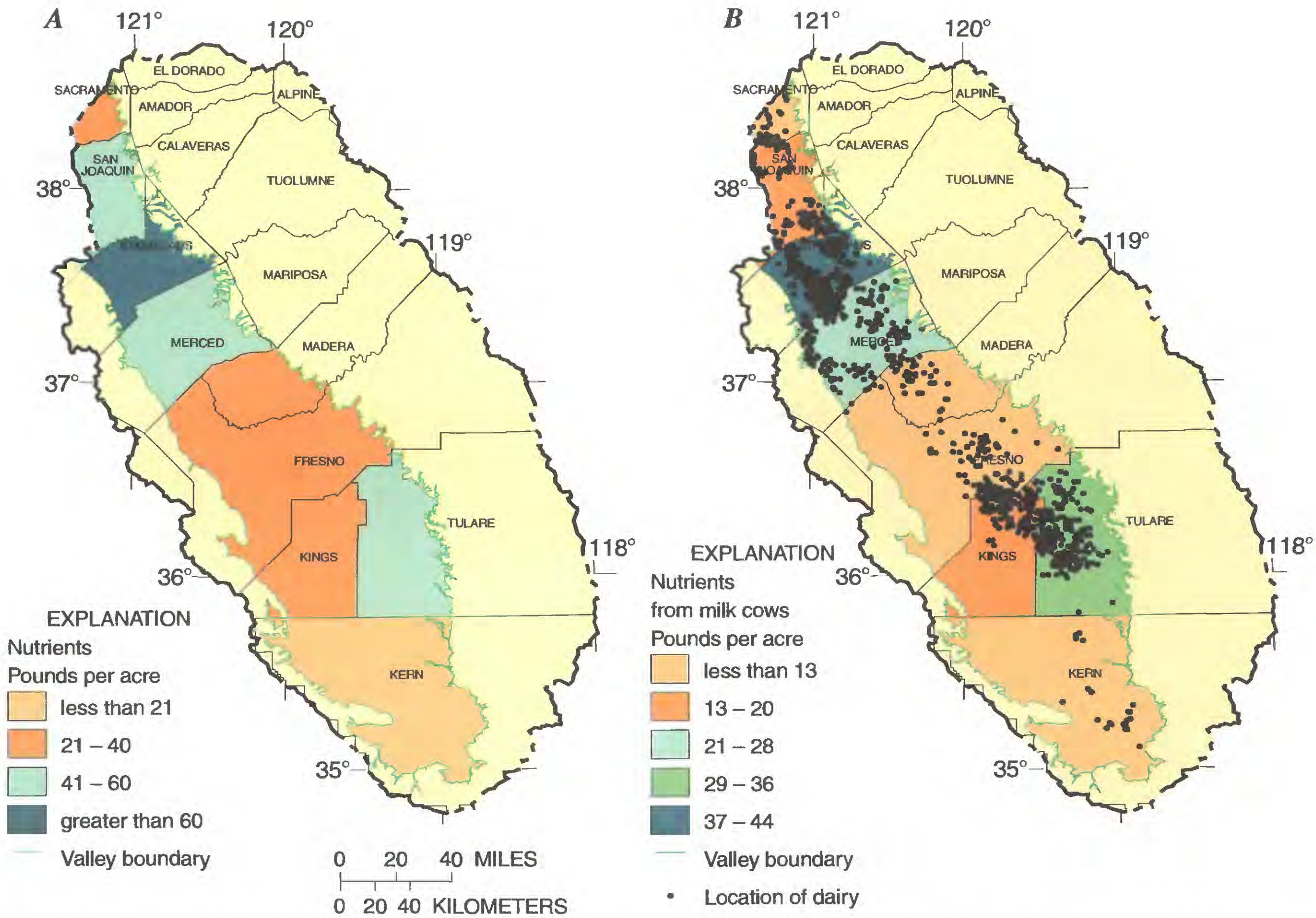

Figure 25. Estimated nutrients in the San Joaquin Valley, California, 1987. (*A*) From manure. (*B*) From milk cow manure, showing location of dairies.

processes affecting selenium in ground water and surface water of the west side of the San Joaquin Valley and the accumulation and resulting toxicity of selenium in waterfowl and aquatic organisms have been studied in detail as part of previous investigations.

Increased pesticide contamination of ground water in the eastern San Joaquin Valley and in surface water in the San Joaquin River and its major tributaries—Roughly 9 percent of nationwide pesticide use is in the San Joaquin–Tulare Basins study unit. Ground water in the eastern part of the valley is susceptible to contamination because of the relatively coarse texture and low organic content of the soils. Pesticides enter the San Joaquin River in runoff from agricultural areas, either in solution or attached to suspended sediments.

Increased nitrate in ground water—Naturally high concentrations of nitrate in soils in the western part of the San Joaquin Valley have leached into parts of the ground-water system. Additionally, fertilizers, manure from livestock, and septic systems throughout the valley are sources of nitrate in ground water.

Reduced concentrations of dissolved oxygen in the San Joaquin River—Low dissolved-oxygen concentrations, attributed to discharge of wastewater from municipal treatment plants, are detrimental to fisheries and other aquatic resources.

Degradation of water quality in the San Joaquin–Tulare Basins study unit affects not only the

2.7 million people in the study unit, but also has the potential to affect about 15 million people in southern California who receive San Joaquin River water through the California Aqueduct (see fig. 3). Coupled with the loss of about 92 percent of the original wetland habitat in the San Joaquin Valley, waterfowl and aquatic life also are affected by degraded water quality. Of the issues listed above, contamination of water resources by pesticides and nutrients were found to be the highest priority national water-quality issues and are the first to be addressed by NAWQA at the national level.

SUMMARY

The San Joaquin–Tulare Basins study unit began, in 1991 to determine the effects of natural and anthropogenic influences on the quality of ground water, surface water, aquatic biology and ecology, as part of the National Water-Quality Assessment (NAWQA) Program.

The San Joaquin–Tulare Basins, which covers approximately 31,200 square miles in central California, is an area of many contrasts. The study unit includes the western slope of the Sierra Nevada to the east, the San Joaquin Valley, and the eastern slope of the Coast Ranges to the west. Altitudes vary greatly from near sea level in the San Joaquin Valley to a maximum altitude of 14,495 feet above sea level at Mount Whitney, which is the highest point in the conterminous United States.

The San Joaquin Valley has an arid-to-semiarid climate that is characterized by hot summers and mild winters. The eastern slopes of the Coast Ranges and the valley are in the rain shadow of the Coast Ranges. The western slopes of the Sierra Nevada receives heavy precipitation, as rain and snow, from the warm, moist air masses from the Pacific Ocean. Annual precipitation in the study unit is highly variable. Similarly, water availability is also highly variable. Based on the state of California water-year classification system, there were seven wet years, three above normal, three dry, and eight critical years between 1972 and 1992.

The San Joaquin River receives water from tributaries draining the Sierra Nevada and Coast Ranges, and except for streams discharging directly to the Sacramento–San Joaquin Delta, is the only surface-water outlet from the study unit. The surface-water hydrology of the San Joaquin–Tulare Basins study unit has been significantly modified by development of water resources. Almost every major river entering the valley from the Sierra Nevada has one or more reservoirs. Almost every tributary and drainage into the San Joaquin River has been altered by a network of canals, drains, and wasteways.

The negative effect of historical changes in land and water use on aquatic biota are most evident when considering the status of the chinook salmon populations. Before large-scale water development and habitat modification, the salmon population was estimated at 300,000 to 500,000 fish. In 1989–1990 less than 3,500 salmon were present in the drainage. Spring-run chinook salmon were eradicated when dams denied them access to cold water pools in upstream areas where they over-summered before spawning in the fall.

The aquifer system of the San Joaquin–Tulare Basins study unit is contained within the southern two-thirds of the Central Valley aquifer system. The aquifer system is made up of Post-Eocene continental rocks and deposits, which contain most of the fresh water in the valley. Two concepts of the aquifer system have been developed, based on the role of the fine-grained lenses on regional flow: (1) an unconfined to semi-confined upper zone separated from a lower confined zone by the Corcoran Clay Member of the Tulare Formation; and (2) a single heterogeneous aquifer with varying vertical leakance and confinement. Regardless of the role of the Corcoran Clay Member in the physical flow system, the contrasts in water chemistry above and below the clay make it an important marker.

Development of the aquifer system began about 1880. Initially, an extensive surface water system was already in place, so ground water provided only a small part of the irrigation water. Eventually, ground-water withdrawal in the Central Valley increased to 11.5 million acre-feet annually in the 1960s and 1970s, providing about half of the irrigation water. The proportion between surface water and ground water used for irrigation varied substantially from wet to dry years. During wet years, inexpensive surface water was used for irrigation; during dry years, ground water predominated.

The bedrock of the Sierra Nevada is primarily granitic. Due to the low solubility of the quartz and feldspars that make up the bulk of these rocks and soils, runoff and snowmelt from the Sierra Nevada have low concentrations of dissolved solids. In

contrast, rocks and sediments of the Coast Ranges in the western part of the study unit contain highly soluble minerals. Of particular importance are marine sedimentary formations with soluble calcium, sodium, and magnesium sulfates, and elevated concentrations of various nitrogen-containing compounds and trace elements. Runoff from the Coast Ranges is sparse, and most of the surface water entering the hydrologic system in the study unit is from the Sierra Nevada and, therefore, generally low in dissolved solids.

The foothills and mountains are covered by rangeland and forests, which are relatively free of anthropogenic influences. In contrast, the San Joaquin Valley is dominated by agricultural land use, which utilized approximately 14.7 million acre-feet of water, and 597 million pounds active ingredient of nitrogen and phosphorus fertilizers in 1990 and 88 million pounds active ingredient of pesticide in 1991. In addition, the livestock industry contributed 318 million pounds active ingredient of nitrogen and phosphorus from manure in 1987.

Irrigation has a large effect on both surface- and ground-water quality because of the large amount of land and water devoted to agriculture. Irrigation return water which reaches surface water and ground water can contain high concentrations of dissolved solids, nutrients, pesticide residues, and trace elements.

The description of the environmental features of the study unit and the possible influences on the water quality in this report, provides background information needed for linking water quality to environmental processes. This, along with the other studies conducted as part of NAWQA, will be of fundamental importance to water-resource managers, planners, and policy makers for strong and unbiased decision-making. By guiding research, monitoring, and regulatory activities, information from NAWQA will contribute to the process of improving the nation's water quality.

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