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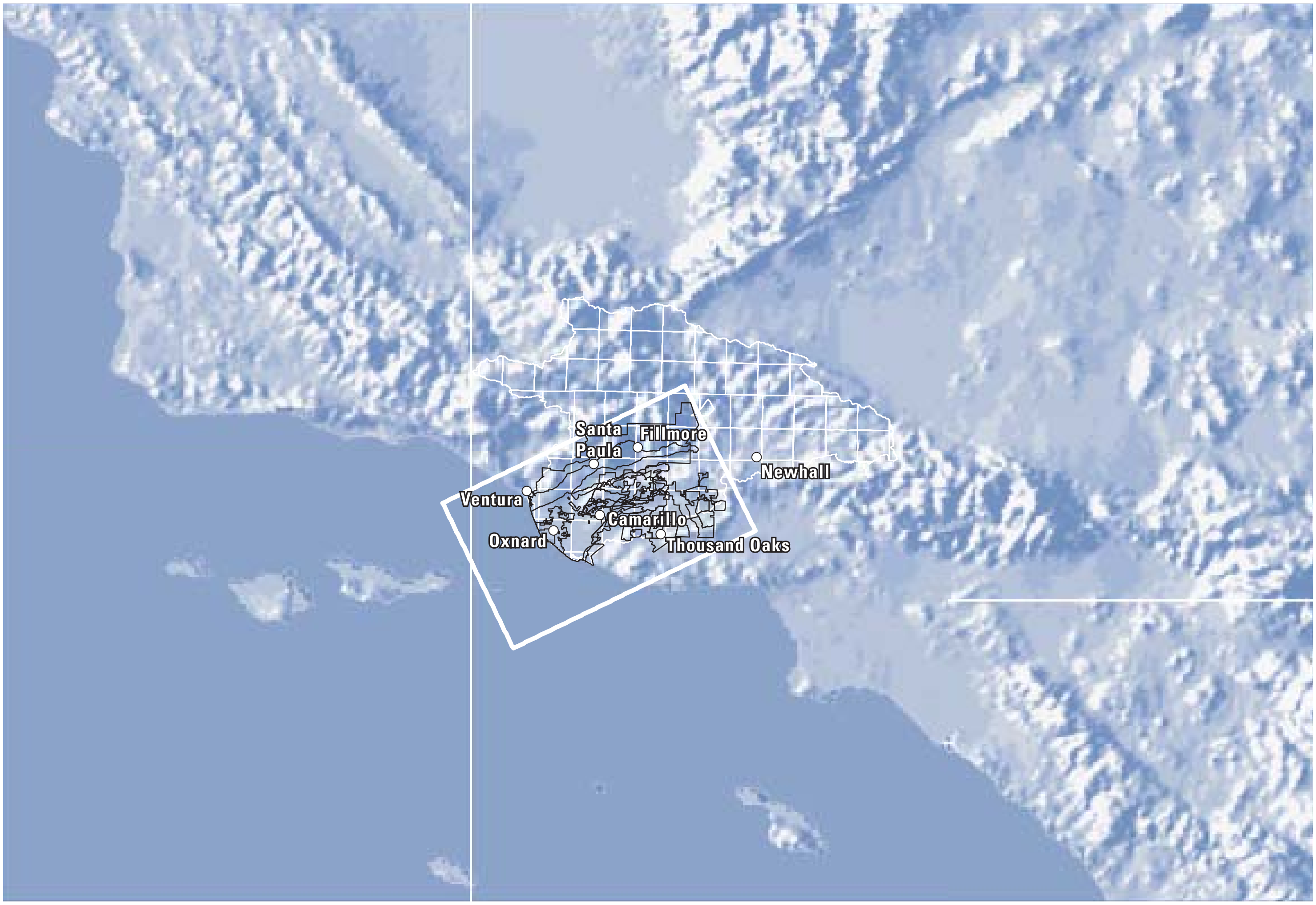

SIMULATION OF GROUND-WATER/ SURFACE-WATER FLOW IN THE SANTA CLARA-CALLEGUAS BASIN, VENTURA COUNTY, CALIFORNIA

A contribution of the
Southern California Regional Aquifer-System Analysis Program

Water-Resources Investigations Report 02-4136

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Simulation of Ground-Water/Surface-Water Flow in the Santa Clara–Calleguas Ground-Water Basin, Ventura County, California

By R.T. HANSON, PETER MARTIN, *and* K.M. KOCZOT

U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS AND WELL-NUMBERING SYSTEM

CONVERSION FACTORS

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
acre	0.4047	hectare
square mile (mi^2)	259.0	hectare
Volume		
acre-foot (acre-ft)	1,233	cubic meter
Flow rate		
acre-foot per day (acre-ft/d)	0.01427	meter per day
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot per year (ft/yr)	0.3048	meter per year
cubic foot per second (ft^3/s)	0.3048	cubic meter per second
foot per day per foot [(ft/d)/ft]	1.0000	meter per day per meter
gallon per minute (gal/min)	0.06309	liter per minute
inch per year (in/yr)	25.4	millimeter per year
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day
Transmissivity		
foot squared per day (ft^2/d)	0.09290	meter squared per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

VERTICAL DATUM

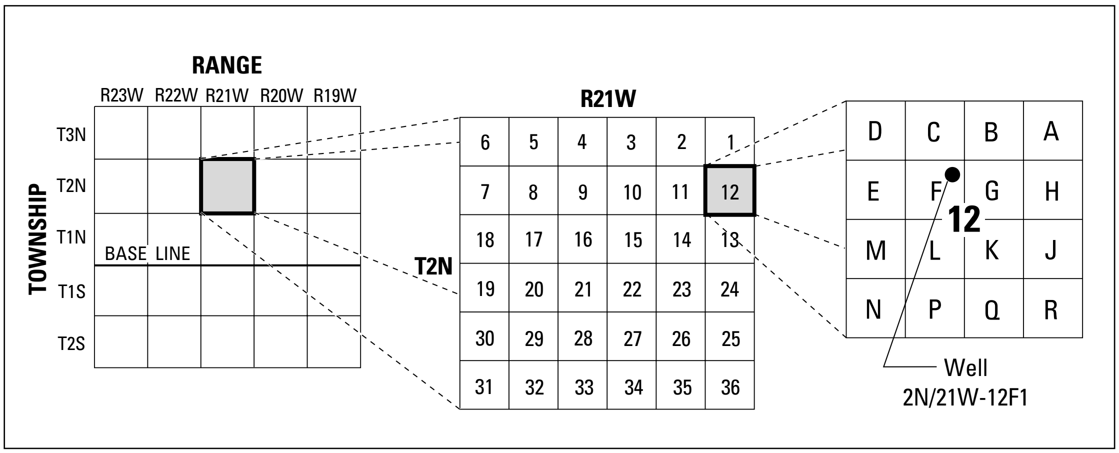
Sea level: In this report, "mean sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviations

AR	autoregressive
ASR	artificial storage and recovery system
BM	bench mark
CMWD	Calleguas Municipal Water District
DWR	[California] Department of Water Resources
EM	electromagnetic induction
ET	evapotranspiration
FGMA	Fox Canyon Groundwater Management District
GIS	Geographic Information System
InSAR	Interferometric Synthetic Aperture Radar
LSA	land surface altitude
ME	mean error
MODFLOW	U.S. Geological Survey's modular flow model
PTP	pumping-trough pipeline
PVCWD	Pleasant Valley County Water District
RASA	Southern California Regional Aquifer-System Analysis
RMSE	root mean square error
SSA	singular-spectrum analysis
STR1	streamflow routing package 1
USGS	U.S. Geological Survey
UWCD	United Water Conservation District
VCFCD	Ventura County Flood Control District
VCPWD	Ventura County Public Works Department

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). Well numbers consist of 15 characters and follow the format 002N002W12F001S. In this report, well numbers may be abbreviated and written 2N/2W-12F1. The following diagram shows how the number for well 2N/2W-12F1 is derived.



Well-numbering diagram

Simulation of Ground-Water/Surface-Water Flow in the Santa Clara–Calleguas Ground-Water Basin, Ventura County, California

By R.T. Hanson, Peter Martin, *and* K.M. Koczot

ABSTRACT

Ground water is the main source of water in the Santa Clara–Calleguas ground-water basin that covers about 310 square miles in Ventura County, California. A steady increase in the demand for surface- and ground-water resources since the late 1800s has resulted in streamflow depletion and ground-water overdraft. This steady increase in water use has resulted in seawater intrusion, inter-aquifer flow, land subsidence, and ground-water contamination.

The Santa Clara–Calleguas Basin consists of multiple aquifers that are grouped into upper- and lower-aquifer systems. The upper-aquifer system includes the Shallow, Oxnard, and Mugu aquifers. The lower-aquifer system includes the upper and lower Hueneme, Fox Canyon, and Grimes Canyon aquifers. The layered aquifer systems are each bounded below by regional unconformities that are overlain by extensive basal coarse-grained layers that are the major pathways for ground-water production from wells and related seawater intrusion. The aquifer systems are bounded below and along mountain fronts by consolidated bedrock that forms a relatively impermeable boundary to ground-water flow. Numerous faults act as additional exterior and interior boundaries to ground-water flow. The aquifer systems extend offshore where they crop out along the edge of the submarine shelf and within the coastal submarine canyons. Submarine canyons have dissected these regional aquifers, providing a hydraulic connection to the ocean through the submarine outcrops of the aquifer systems. Coastal landward flow (seawater intrusion) occurs within both the upper- and lower-aquifer systems.

A numerical ground-water flow model of the Santa Clara–Calleguas Basin was developed by the U.S. Geological Survey to better define the geohydrologic framework of the regional ground-water flow system and to help analyze the major problems affecting water-resources management of a typical coastal aquifer system. Construction of the Santa Clara–Calleguas Basin model required the compilation of geographic, geologic, and hydrologic data and estimation of hydraulic properties and flows. The model was calibrated to historical surface-water and ground-water flow for the period 1891–1993.

Sources of water to the regional ground-water flow system are natural and artificial recharge, coastal landward flow from the ocean (seawater intrusion), storage in the coarse-grained beds, and water from compaction of fine-grained beds (aquitards). Inflows used in the regional flow model simulation include streamflows routed through the major rivers and tributaries; infiltration of mountain-front runoff and infiltration of precipitation on bedrock outcrops and on valley floors; and artificial ground-water recharge of diverted streamflow, irrigation return flow, and treated sewage effluent.

Most natural recharge occurs through infiltration (losses) of streamflow within the major rivers and tributaries and the numerous arroyos that drain the mountain fronts of the basin. Total simulated natural recharge was about 114,100 acre-feet per year (acre-ft/yr) for 1984–93: 27,800 acre-ft/yr of mountain-front and bedrock recharge, 24,100 acre-ft/yr of valley-floor recharge, and 62,200 acre-ft/yr of net streamflow recharge.

Artificial recharge (spreading of diverted streamflow, irrigation return, and sewage effluent) is a major source of ground-water replenishment. During the 1984–93 simulation period, the average rate of artificial recharge at the spreading grounds was about 54,400 acre-ft/yr, 13 percent less than the simulated natural recharge rate for streamflow infiltration within the major rivers and tributaries. Estimated recharge from infiltration of irrigation return flow on the valley floors averaged about 51,000 acre-ft/yr, and treated sewage effluent averaged about 9,000 acre-ft/yr. Artificial recharge as streamflow diversion to the spreading grounds has occurred since 1929, and treated-sewage effluent has been discharged to stream channels since 1930.

Under predevelopment conditions, the largest discharge from the ground-water system was outflow as coastal seaward flow and evapotranspiration. Pumpage of ground water from thousands of water-supply wells has diminished these outflows and is now the largest outflow from the ground-water flow system. The distribution of pumpage for 1984–93 indicates that most of the pumpage occurs in the Oxnard Plain subareas (37 percent) and in the upper Santa Clara River Valley subareas (37 percent). The total average simulated pumpage was about 247,000 acre-ft/yr (59 percent); of which about 146,000 acre-ft/yr was from the Fox Canyon Groundwater Management Agency (FGMA) subareas and 101,000 acre-ft/yr (41 percent) from the non-FGMA subareas. Of the total 1984–93 pumpage, 46 percent was contributed by natural recharge, 22 percent was contributed by artificial recharge from diverted streamflow, 20 percent was contributed by irrigation return flow, 4 percent was contributed from sewage-effluent infiltration, 6 percent was contributed from storage depletion, and 2 percent was contributed from coastal landward flow (seawater intrusion).

Seawater intrusion was first suspected in 1931 when water levels were below sea level in a large part of the Oxnard Plain. The simulation of regional ground-water flow indicated that coastal landward flow (seawater intrusion) began in 1927 and continued to the end of the period of simulation (1993). During wet periods or periods of reduced demand for ground water, the direction of coastal flow in the upper-aquifer system reverses from landward to seaward. During the 1984–93 period, the simulated total net seaward flow was 9,500 acre-feet in the upper-aquifer system, which is considerably less than that simulated for predevelopment conditions. During the same period, total simulated landward flow in the lower-aquifer system was 64,200 acre-feet.

Water-level declines in the basin have induced land subsidence that was first measured in 1939 and have resulted in as much as 2.7 feet land subsidence in the southern part of the Oxnard Plain. The model simulated a total of 3 feet of land subsidence in the southern part of the Oxnard Plain and as much as 5 feet in the Las Posas Valley subbasins. Model simulations indicate that most of the land subsidence occurred after the drought of the late 1920s and during the agricultural expansion of the 1950s and 1960s. The results also indicate that subsidence occurred primarily in the upper-aquifer system prior to 1959, but in the lower-aquifer system between 1959–93 owing to an increase in pumpage from the lower-aquifer system.

The calibrated ground-water flow model was used to assess future ground-water conditions based on proposed water-supply projects in the existing management plan for the Santa Clara–Calleguas ground-water basin. All the projections of the proposed water-supply projects in the existing management plan have reduced pumpage in the FGMA areas which resulted in a reduction but not an elimination of storage depletion and related coastal landward flow (seawater intrusion) and subsidence, a reduction in streamflow recharge, and an increase in coastal seaward flow and underflow to adjacent subareas from the Oxnard Plain. A comparison of management simulations based on historical inflows and a spectral estimate of inflows shows increased coastal landward flow (seawater intrusion), storage depletion, and increased land subsidence due to a drought projected earlier in the spectral estimate of inflows than in the historical inflows. The spectral estimate probably provides a smoother and more realistic transition between historical and future climatic conditions.

The model also was used to simulate potential alternative water-supply projects in the Santa Clara–Calleguas ground-water basin. These seven alternative water-supply projects were proposed to help manage the effects of increasing demand and variable supply on seawater intrusion, subsidence, increased withdrawal from storage, and vertical and lateral flow between subareas and aquifers systems. Stopping pumpage primarily in the lower-aquifer system in the South Oxnard Plain subarea had the largest effect on reducing coastal landward flow (seawater intrusion) of all the potential cases evaluated. Shifting pumpage from the lower- to the upper-aquifer system in the South Oxnard Plain subarea yielded the largest combined effect on coastal flow with a reduction of coastal landward flow in the lower-aquifer system and coastal seaward flow from the upper-aquifer system. A seawater-barrier injection project stopped coastal landward flow (seawater intrusion) in the upper-aquifer system but also resulted in large quantities of coastal seaward flow. The recharge of water in Happy Camp Canyon resulted in water-level rises that were above land surface (not feasible) in the East Las Posas Valley subarea but in no significant changes in hydrologic conditions in other parts of the basin.

INTRODUCTION

Ground water from the regional alluvial-aquifer systems is the main source of water in the Santa Clara and Calleguas watersheds in southern California. In Ventura County, for the purposes of this study, the alluvial ground-water basins of these watersheds are referred to as the Santa Clara–Calleguas ground-water basin. Development of the water resources of the Santa Clara–Calleguas ground-water basin has steadily increased since the late 1800s, resulting in streamflow depletion, ground-water overdraft, seawater intrusion, inter-aquifer flow, land subsidence, and ground-water contamination. The extent of ground-water overdraft, which is the withdrawal of potable water from an aquifer system in excess of replenishment from natural and artificial recharge, varies throughout the basin. Overdraft is also dependent on climatic variability and associated increases in water use. Overdraft has been larger within selected subareas of the ground-water basin and in the deeper aquifers. However, there has been an increased amount of conjunctive use to compensate for the effects of the variability of surface-water supplies and to mitigate the effects of ground-water overdraft.

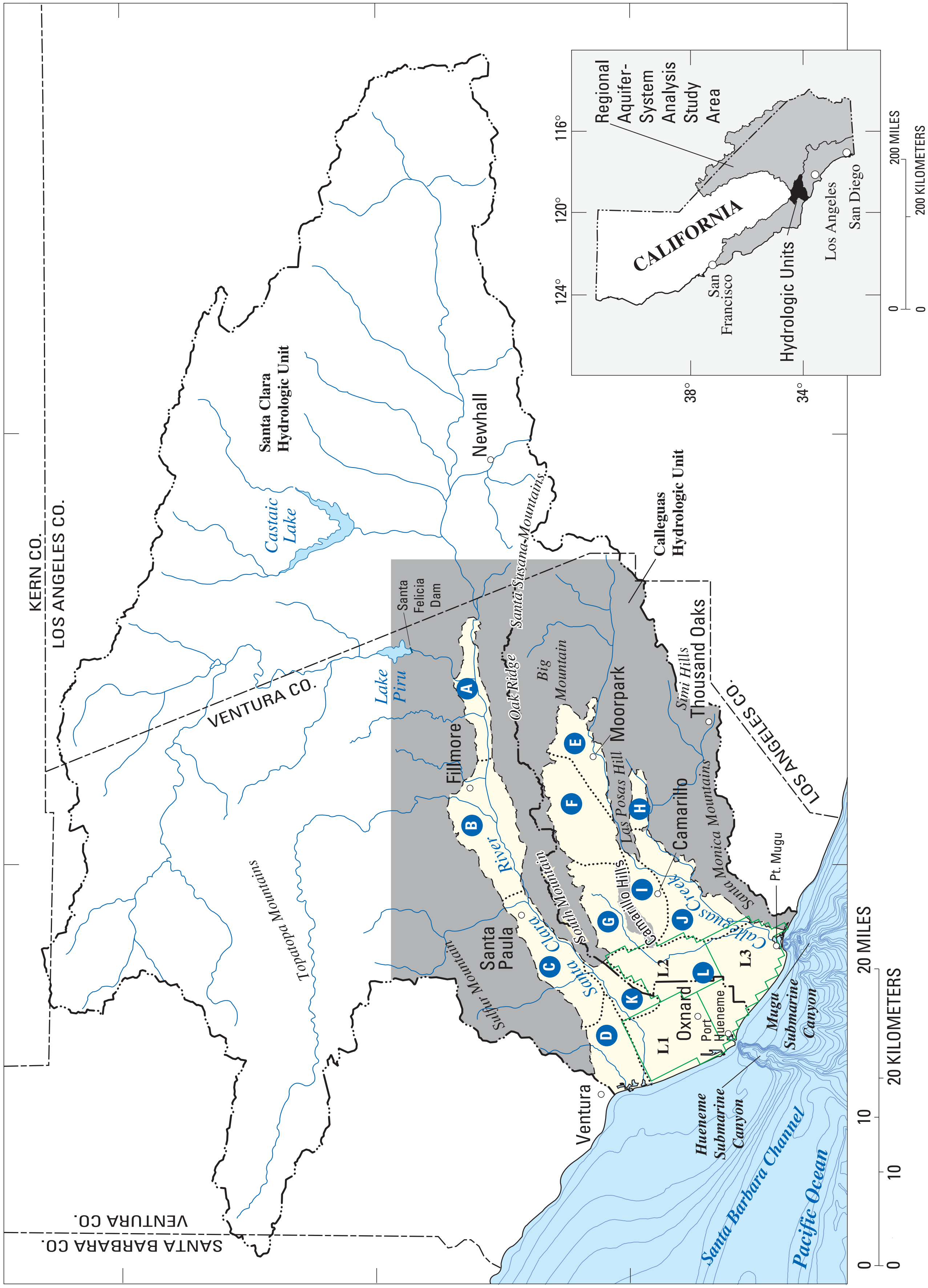
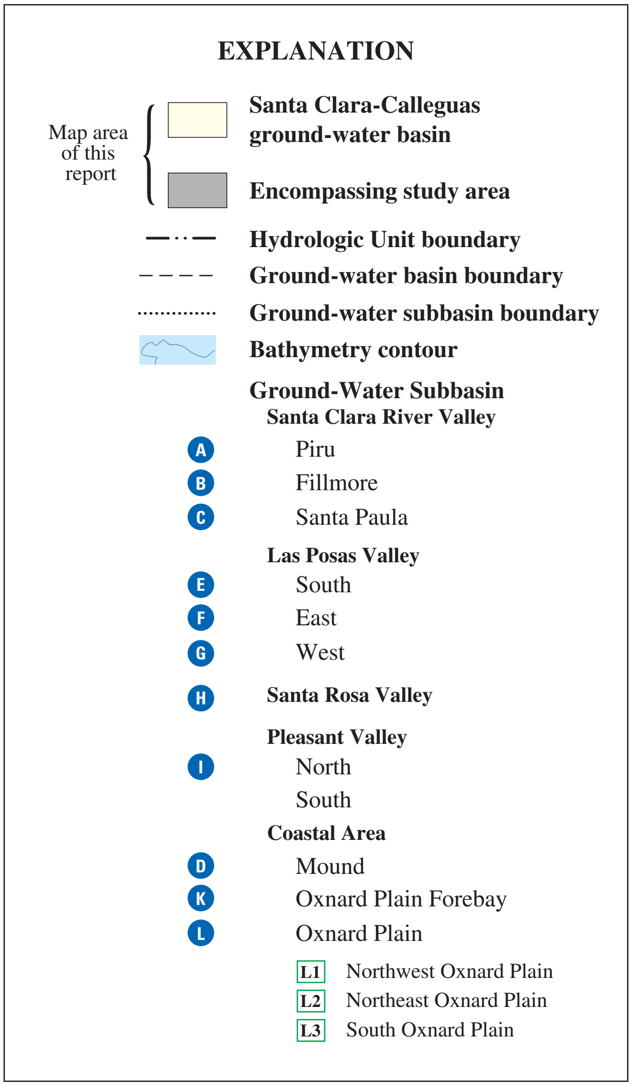


Figure 1. Santa Clara–Calleguas Hydrologic Unit and ground-water basin. (Modified from California State Water Resources Board, 1956)



A U.S. Geological Survey (USGS) study of the hydrogeology of the Santa Clara–Calleguas Basin was completed as part of the Southern California Regional Aquifer-System Analysis (RASA) Program (Martin, 1986). The purpose of the Southern California RASA Program was to analyze the major problems and issues affecting ground-water use in southern California, including ground-water overdraft, streamflow depletion, subsidence, seawater intrusion, and ground-water contamination. Because of the large size of the study area and the large number of basins involved, only two, the Santa Clara–Calleguas Basin (coastal) and the Mojave River ground-water basin (desert), of the 89 hydrologic subunits identified by the California Department of Water Resources (1964) were studied for the Southern California RASA Program (Martin, 1993). The basic assumption of the program was that certain characteristics of the geohydrologic processes and human activities that control or influence water resources are common to many of the basins or groups of basins. The development of the Santa Clara–Calleguas Basin study is an extension of previous investigations in the nearby coastal aquifer systems in Santa Barbara, California (Martin and Berenbrock, 1986; Freckleton and others, 1998).

Purpose and Scope

The purpose of this study is to acquire a better understanding of the hydrogeologic system in the Santa Clara–Calleguas Basin (fig. 1) and to develop a tool to help analyze the major problems affecting water-resources management of a typical coastal aquifer system. The study included a reevaluation of the basin structure and stratigraphy of the water-bearing rocks and an evaluation of the hydrologic system under predevelopment, historical development, and future development conditions. The purposes of this report are to describe the regional ground-water flow model that was constructed for the RASA Program, to summarize the results of simulations of historical and future periods using the RASA model, and to describe the model limitations and the data needed for future model refinements. Also described in this report are ground-water recharge, movement, and discharge.

Approach

A regional model of ground-water flow that simulates the hydrologic system under pre- and post-development conditions was developed to evaluate the natural and human-induced controls on the regional water resources. Because water-resources development began relatively early in the coastal basins of California, there is very little quantitative information on predevelopment ground-water and surface-water conditions. This lack of data required coupling the calibration of the steady- and transient-state simulations to arrive at a combined fit for pre- and post-development conditions.

Previous studies of the aquifer systems (Mann and Associates, 1959; Turner, 1975) and numerical models of the hydrologic system (California Department of Water Resources, 1974a,b; Reichard, 1995) were used as the starting point for the reevaluation of the stratigraphy and structure of the water-bearing units and to provide estimates of hydraulic properties of each unit. Reevaluation was based on additional geophysical data, geochemical data, and hydraulic data from selected existing production wells and from 23 new monitoring wells drilled throughout the basin by the USGS (Izbicki and others, 1995; Densmore, 1996). Estimates for many of the hydraulic properties and for the quantities and locations of recharge and discharge needed to simulate ground-water flow in the major water-bearing units generally were unavailable; therefore, indirect estimates, which were modified during the calibration of the numerical model, were required.

Description of Study Area

The Santa Clara (hydrologic unit 18070102) and Calleguas (hydrologic unit 18070103) Basins are coastal watersheds that principally drain parts of Ventura and Los Angeles Counties; they have a total drainage area of 2,010 mi^2 (fig. 1). Almost 90 percent of the basin surface is characterized by rugged topography; the remainder consists of valley floor and coastal plain composed of a northeast-trending set of anticlinal mountains and synclinal valleys in the Transverse Ranges physiographic province. The onshore part of the Santa Clara–Calleguas alluvial basin is about 32 mi long and includes about 310 mi^2. The ground-water basin extends as much as 10 miles offshore and includes an additional 193 mi^2. The sloping offshore plain and underlying aquifers are truncated by steeply dipping submarine cliffs that are dissected by several submarine canyons.

The Santa Clara–Calleguas Basin is a regional ground-water basin that can be divided into 12 onshore subbasins (fig. 1). The coastal subbasins extend offshore beneath the gently sloping submarine shelf. The ground-water subbasins are subareas within the surface-water drainage subbasins, and many of their boundaries are aligned with known faults and other geologic features. The Piru, Fillmore, Santa Paula, and Mound subbasins and the northern part of the Oxnard Plain known as the Oxnard Plain Forebay subbasin compose the Santa Clara River Valley. The Santa Rosa Valley, East and South Las Posas Valley, and North and South Pleasant Valley subbasins and the southern part of the Oxnard Plain subbasin compose the Arroyo Simi–Arroyo Las Posas–Conejo Creek–Calleguas Creek drainage basin. In the West Las Posas Valley subbasin, Arroyo Hondo and Beardsley Wash flow into Revolon Slough, which flows along with Calleguas Creek into Mugu Lagoon (see figure 4 in the “Surface Water” section). These three drainages cross parts of the coastal subbasin known as the Oxnard Plain.

The Santa Clara River and the Calleguas Creek discharge directly to the Pacific Ocean. The onshore ground-water basin is bounded by the Sulfur Mountain and the Topatopa Mountains on the north, the Santa Susana Mountains and the Simi Hills on the east, and the Santa Monica Mountains on the south (fig. 1). Mountain peaks, which exceed 6,700 ft in altitude, rise above numerous narrow valleys and streams that are tributary to the Santa Clara River and Calleguas Creek drainage basins. The west-trending Oak Ridge, South Mountain, and Santa Susana Mountains separate the Santa Clara River Valley from the Las Posas Valley. The west-trending Las Posas and Camarillo Hills separate Las Posas Valley from Pleasant Valley. These intermontane alluvial valleys grade into the coastal flood plains in the Oxnard Plain and the Mound subbasins. The coastal flood plain continues offshore as a gently sloping submarine shelf of the Santa Barbara Channel. The submarine shelf is bounded on the west by steeply sloping submarine cliffs where the water-bearing formations crop out. The shelf is dissected by the Hueneme and the Mugu submarine canyons and several unnamed smaller submarine canyons (fig. 1). The larger submarine canyons dissect the submarine shelf to the present-day shoreline.

Climate

The climate of the basin is of the mediterranean type with 85 percent of the rainfall occurring between November and April, typical of the southern California coastal area. Average annual precipitation is about 14 in. at Port Hueneme along the coast, about 17 in. near Santa Paula in the intermediate altitudes of the Santa Clara River Valley, and more than 25 in. in the surrounding mountains (Ventura County Public Works Agency, 1990, 1993). Daily mean temperatures range from as high as 89°F along the coast in late summer and early fall to below freezing in the bordering mountains during winter. Mean pan-evaporation rates range from 59 in/yr at Casitas Dam at Ventura County Flood Control District (VCFCD) Station Number 4 to 73 in/yr at Lake Bard at VCFCD Station Number 227 (Ventura County Public Works Agency, 1990, 1993).

The climate is seasonally variable and has been variable through time (fig. 2). The cumulative departure of tree-ring indices and precipitation can be used to divide periods of the climatic record into wet and dry climatic periods. Wet climatic periods are determined using the rising limb of the cumulative departure curve, and dry climatic periods are determined using the falling limb of the cumulative departure curve. The cumulative departure of tree-ring indices for southern California for 1458–1966 (National Atmospheric and Oceanic Administration, 1994) indicates an apparent shift in the frequency and amplitude of wet and dry periods after the early 1700s. Prior to the early 1700s, wet and dry periods were relatively long (20 to more than 60 years); whereas after the early 1700s, wet and dry periods were shorter (5 to 20 years) (fig. *2A*). The wet and dry periods determined from tree-ring indices for 1770–1965 generally are in agreement with available precipitation records for Port Hueneme and Santa Paula and are related to periods of major droughts and floods (fig. 2B).

Population

The Santa Clara–Calleguas Basin was settled and populated by Native American Indians of the Shumash Tribes. Spanish missionaries established Mission San Buena Ventura in 1787. In the early 1800s, Jesuit Fathers from the San Buena Ventura Mission established an asistencia (Ventura Mission outpost) where the city of Santa Paula is now located (Freeman, 1968). These colonies and related Spanish land grants developed the initial agrarian and ranching industry in the river valleys. The town of San Buena Ventura (hereinafter referred to as “Ventura”) became the county seat. By 1930, Ventura County had a total population of 54,976; Ventura and Santa Paula were the most populous cities. Ventura, which was largely supported by the oil industry, had a population of 11,603. Santa Paula and Fillmore, which were the principal towns in the citrus area, had populations of 7,452 and 2,890, respectively. Oxnard, the center of the beet-sugar industry in Ventura County, had a population of 6,285 (California Department of Public Works, 1934). By 1970, the population in Ventura County increased to 378,497 as various small unincorporated settlements grew into towns. The population increased to 535,700 by 1980, and to 686,900 by 1992—a 28 percent increase. Since the 1960s, a large part of the population increase was related to the urbanization of Ventura County.

Land and Water Use

Prior to the 1900s, most land in the Santa Clara–Calleguas Basin was used for grazing cattle and dry-land farming. In the early 1900s, agricultural and petroleum production became the chief economic activities. As in all the coastal basins, urbanization since the late 1940s resulted in the transfer of agricultural lands to residential and commercial uses, especially in the Oxnard Plain. In the late 1940s, the turbine pump was introduced for pumping ground water, and in the early 1950s, the introduction of the refrigerated railroad car provided long-range markets for fresh produce. As a result, agriculture was transformed from predominantly seasonal dry-land farming of walnuts and field crops to predominantly year-round irrigated farming of citrus, avocados, and truck crops, and water use increased to a historical high during the 1950s. Currently, about 80 percent of the ground-water and surface-water supply is used for agriculture. Agricultural land use increased less than 5 percent and urban land use increased from 39 to 51 percent between 1969 and 1980. Since 1980, urban growth has continued and urban land use has remained the dominant land use in the basin. Because of the proximity to the Los Angeles metropolitan area, growth may continue with further transformation from an agriculture-based economy to an urban and industrial economy. An excellent summary of the development of water in Ventura County is given by Freeman (1968).

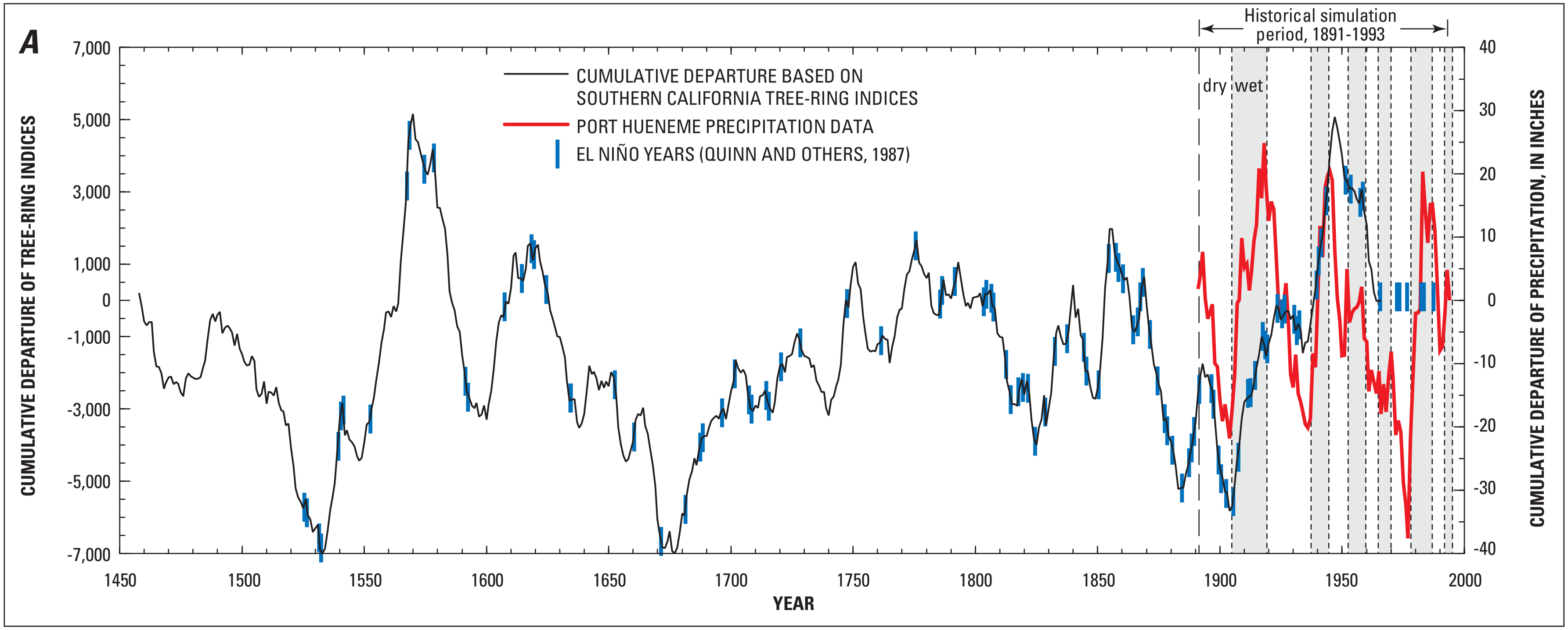


Figure 2. ***A***, Cumulative departure of tree-ring indices for southern California (1458–1966), cumulative departure of precipitation at Port Hueneme (1891–1993), and wet and dry climatic periods for the historical simulation period (1891–1993), and ***B***, Cumulative departure of tree-ring indices for southern California, cumulative departure of precipitation at Port Hueneme and Santa Paula, wet and dry climatic periods, and major climatic events (1770–1965), Ventura County, California.

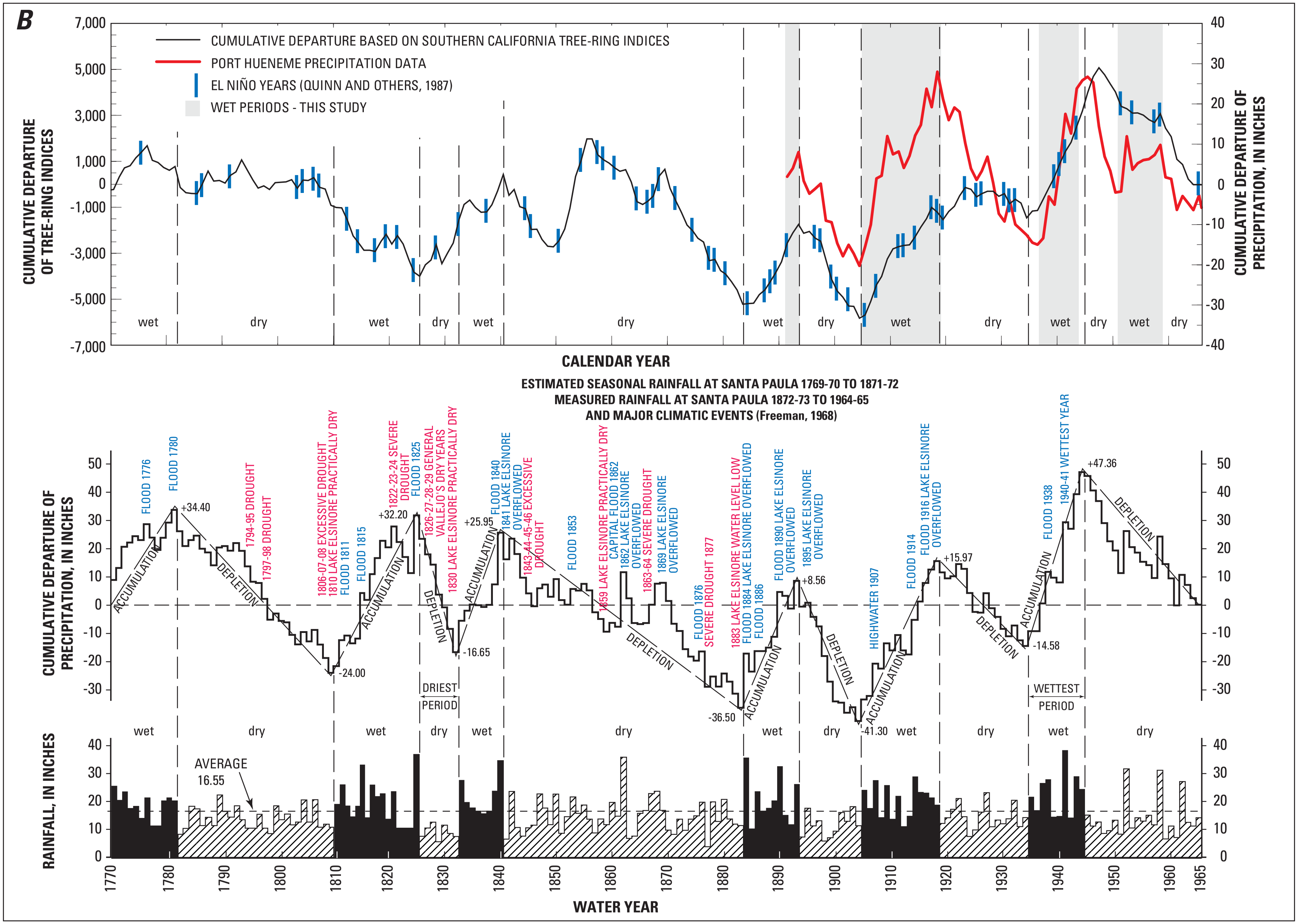


Figure 2. Continued.

Acknowledgments

This study could not have been accomplished without the assistance of personnel from the United Water Conservation District (UWCD), the hydrology section of the Ventura County Public Works Department (VCPWD), the Fox Canyon Groundwater Management Agency (FGMA), the Calleguas Municipal Water District (CMWD), the U.S. Department of the Navy, the Pleasant Valley County Water District (PVCWD), local municipalities and water mutuals, and numerous other well owners that provided data and allowed access to their wells for sampling and well testing. The authors are also indebted to Wesley Danskin, USGS, for assistance with the modifications to the diversion component of the streamflow-routing package (Appendix 2), and to Michael Dettinger, USGS, for assistance with the analysis of historical precipitation and estimation of future precipitation (Appendix 3). The authors would also like to thank Larry Schneider for his extraordinary effort in creating the scientific illustrations for this report. An additional special thanks also goes out to Myrna L. DeBortoli and Mary Gibson for editing this large and complicated report.

SURFACE WATER

Runoff from precipitation in the upland areas that surround the Santa Clara–Calleguas Basin is the predominant source of natural streamflow and ground-water recharge. As agriculture developed, some streamflow was diverted for irrigation. Since the 1950s, imported water from northern California has been combined with local surface water and collectively used for artificial recharge. Discharge of reclaimed sewage effluent, which began in the late 1930s, provides an additional source of water to the surface-water and ground-water systems in parts of the basin.

Precipitation Estimates

Precipitation, and related surface-water flow, has been variable through time, and is the major source of ground-water recharge. For this study, precipitation and streamflow data and statistical relations determined from these data were segregated into wet and dry seasonal periods to reconstruct historical runoff and streamflow. The cumulative departure curve of precipitation for Port Hueneme was used to divide periods of record into wet and dry climatic periods (fig. 2). The wet and dry climatic periods were determined using the rising and falling limbs of the cumulative departure curve, respectively.

As noted earlier, for the past few centuries, cumulative departure of the tree-ring indices for southern California indicates an apparent shift in the frequency and amplitude of the wet and dry periods after the early 1700s; prior to the early 1700s wet and dry periods were relatively long (20 to more than 60 years) whereas after the early 1700s these periods were relatively short (5 to 20 years) (fig. *2A*). Frequency analyses (spectral) of tree rings, precipitation, and ground-water levels indicate climatic cycles of 22, 5.3, and 2.2–2.9 years for the period of record (Appendix 3; Hanson and Dettinger, 1996). Collectively, these cycles account for 60 percent of the variation in precipitation. Winter and spring rainfall is derived largely from arctic-northern frontal storms that may be related to the long term (22 year) climatic cycles of the Pacific decadal oscillation. Intermediate (5.3 year) cycles contribute to fall and winter rainfall and may be related to a combination of storms related to a northerly flow of moisture from El Niño and monsoonal flow from the central Pacific Ocean. Additional moisture may be associated with meridianal flow of the jetstream and related extracyclonic storms that occur during the short-term (2.2–2.9 year) cycles of El Niño years in both wet and dry periods (fig. *2A*). Examples of exceptional storm-type related events that may be attributed to subtropical extracyclonic storms include a short-lived, intense rain storm, such as occurred in September of 1910 during a dry period; a relatively wet year, such as 1962, during a dry period; and historic flooding, such as in 1853. Freeman (1968) originally segregated wet and dry periods on the basis of precipitation records from Santa Paula and precipitation estimates reconstructed from crop indices for 1769 through 1965. Freeman demonstrated a strong correlation between the longer term wet and dry periods and observed hydrologic events in southern California, such as changes in stage of lakes and reservoirs, and droughts and floods (fig. *2B*).

For this study, six alternating climate cycles that resulted in six wet and six dry periods between 1891 and 1993 were identified on the basis of the cumulative departure curve for precipitation measured at Port Hueneme (fig. 2*A*). The climate cycles were separated into wet-year and dry-year periods as follows:

CYCLE	DRY-YEAR PERIOD	WET-YEAR PERIOD
1	1891–1904	1905–1918
2	1919–1936	1937–1944
3	1945–1951	1952–1958
4	1959–1964	1965–1969
5	1970–1977	1978–1986
6	1987–1991	1992–1993

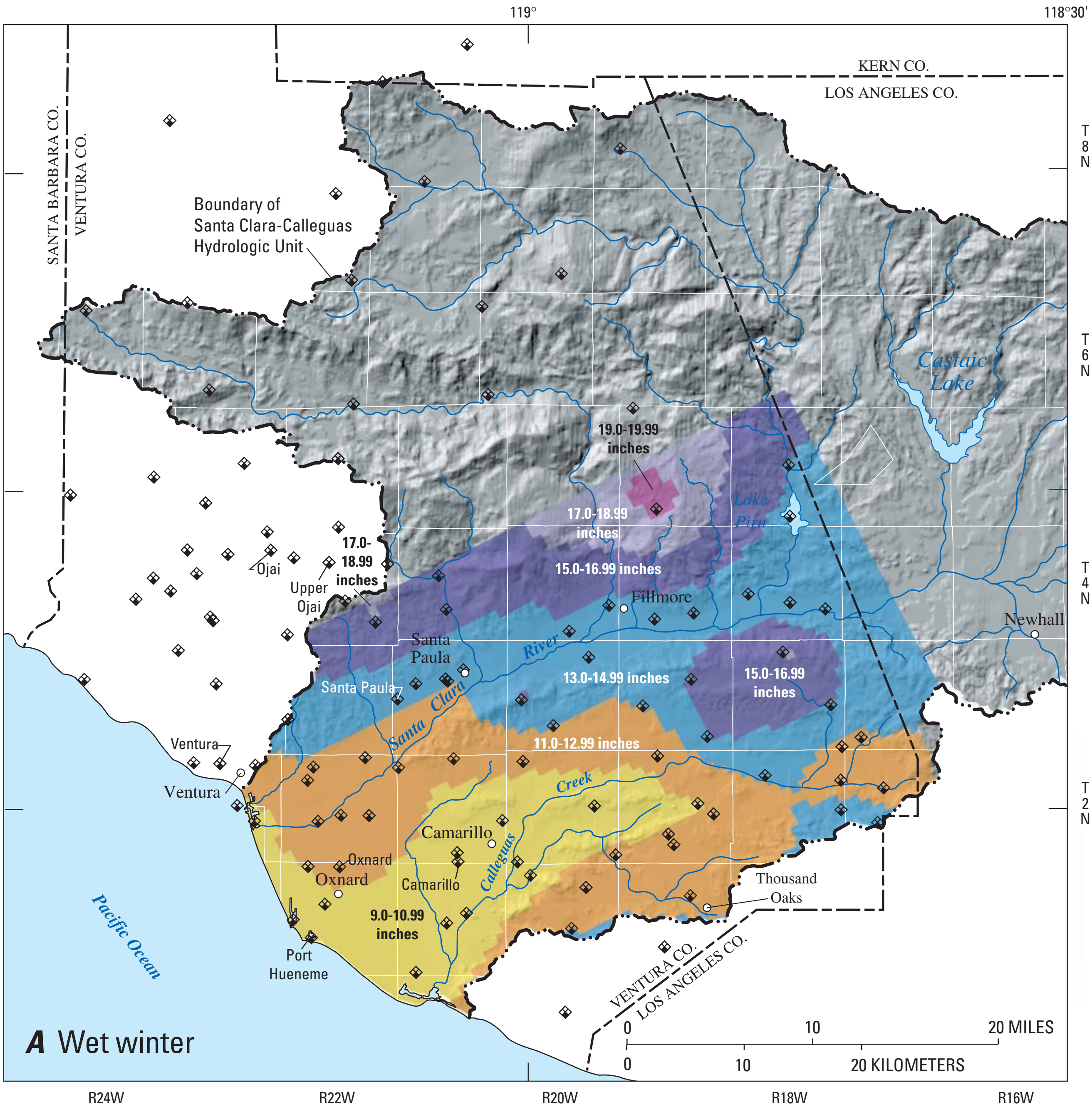
This segregation shows good agreement with the tree-ring indices and the climate periods delineated by Freeman (1968) (fig. 2*A*,*B*). Selected coastal precipitation stations at Ventura, Oxnard, Port Hueneme, and Camarillo were used to assess the segregation of data within the wet- and dry-year seasons (fig. 3, table 1). Although there are some wet years in dry periods and dry years in wet periods, the seasonal mean coastal precipitation for these multiple-year wet- and dry-year period groupings is not significantly different from the seasonal mean precipitation grouped for individual wet and dry years (independent of wet- and dry-year periods) but is significantly different from the period-of-record mean for all seasons except summer (table 1). This general segregation of recent historical climatic variability into wet- and dry-year periods were used to reconstruct the historical estimates of precipitation and streamflow. Ground-water recharge and changes in ground-water demand measured or estimated from pumpage data were categorized on the basis of these wet and dry periods.

Kriged estimates of average total seasonal precipitation for wet and dry winters, springs, summers, and falls were made from available data from the Ventura County Flood Control District precipitation stations for 1891 to 1991 (fig. 3*A*–*H*). Data were not available for individual stations for the entire period of estimation. The spatial distributions of seasonal precipitation for wet and dry periods were similar for winter and fall. Spring and summer precipitation patterns, however, showed a small shift from relatively more precipitation in the northern mountains during wet springs and summers to relatively more precipitation in the southeastern mountains during dry springs and summers (fig. 3*C*–*F*). The largest increase in seasonal precipitation was between wet and dry winters (fig. 3*A*,*B*). The ratio of wet- to dry-season precipitation was 1.8 for winter, 1.6 for spring, 1.1 for summer, and 1.2 for fall.

Streamflow

The Santa Clara River Basin drains the area to the north and east of the Santa Clara–Calleguas ground-water basin; its major tributaries are Piru, Hopper, Pole, Sespe, Santa Paula, and Ellsworth Creeks (fig. 4). Calleguas Creek and its major tributaries, Conejo Creek and Arroyo Simi–Las Posas, drain the areas to the south and east of the alluvial basin. Revolon Slough and its major tributaries, Arroyo Hondo and Beardsley Wash (fig. 4), drain the western part of the Las Posas Valley and the southwestern part of the Oxnard Plain. Streamflow represents the major natural source ground-water recharge to the basin. The steadily increasing use of the surface-water and ground-water resources of the Santa Clara–Calleguas Basin since the late 1800s has resulted in streamflow depletion.

Streamflow measurements were made as early as the late 1800s (Grunsky, 1925), but continuous measurement at permanent gaging stations was not undertaken until 1912 on Piru Creek and not until 1927 on the Santa Clara River (fig. 4). Gaging stations also were established on other Santa Clara River tributaries (fig. 4) starting in 1927. Streamflow gaging stations were first established on the Arroyo Simi in 1934 and on Conejo Creek in the 1970s. Continuous gaging of streamflow at downstream sites began at Montalvo on the Santa Clara River (11114000) in 1955, on the Calleguas Creek above U.S. Highway 101 (11106550) in 1971, and at Camarillo (11106000) in 1968 (fig. 4).



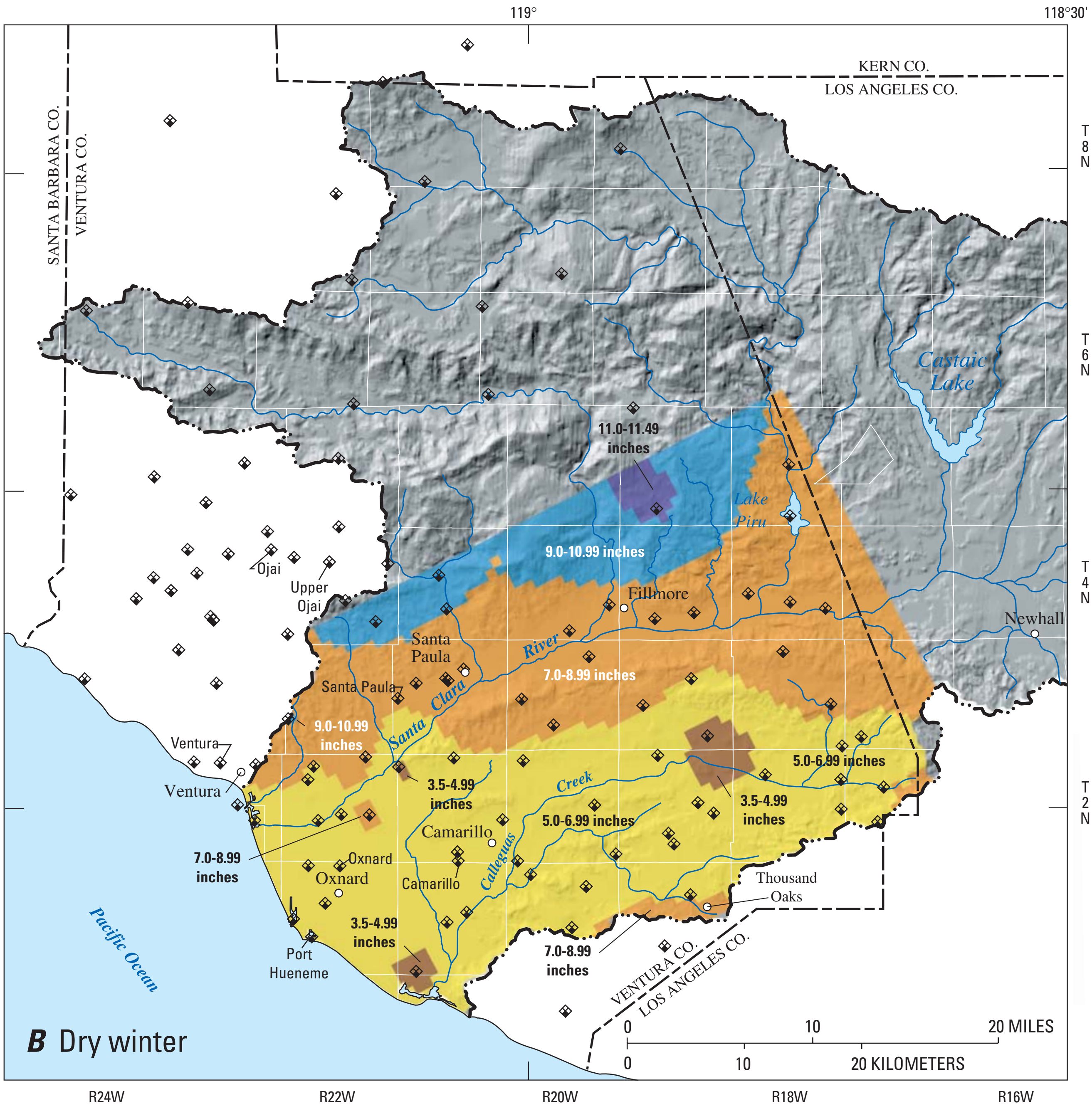
EXPLANATION

9.0-10.99 inches **Precipitation –** Numbers show range in kriged average total seasonal precipitation for each colored subregion.

Oxnard ◈ **Ventura County Flood Control District precipitation station with selected names**

○ **City or town**

Figure 3. Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***A***, Wet winter. ***B***, Dry winter. ***C***, Wet spring. ***D***, Dry spring. ***E***, Wet summer. ***F***, Dry summer. ***G***, Wet fall. ***H***, Dry fall. Number of seasons available varies between stations.



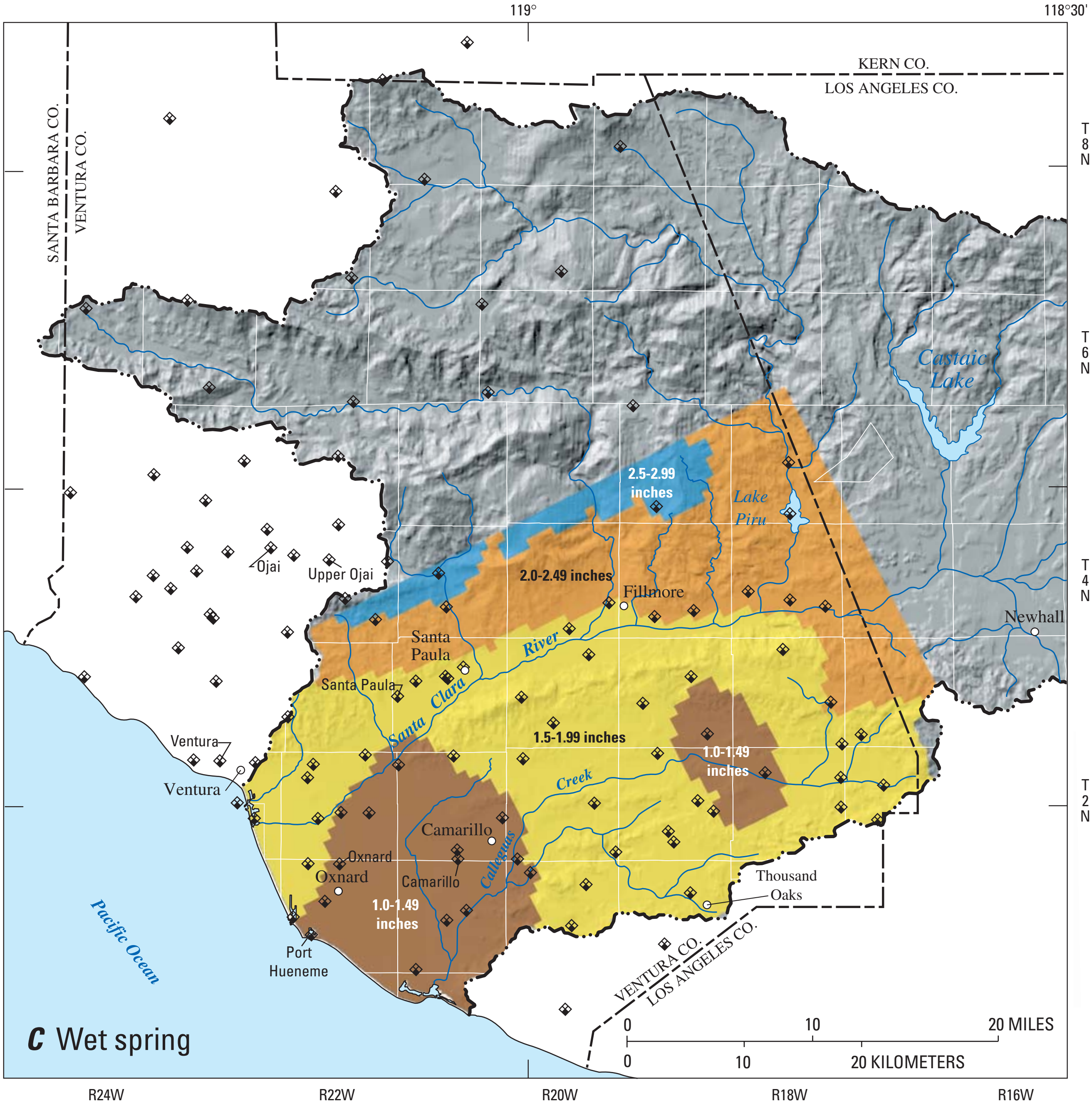
EXPLANATION

9.0-10.99 inches **Precipitation –** Numbers show range in kriged average total seasonal precipitation for each colored subregion.

Oxnard ◈ **Ventura County Flood Control District precipitation station with selected names**

○ **City or town**

Figure 3—Continued. Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***B***, Dry winter.



EXPLANATION

1.0-1.49 inches **Precipitation –** Numbers show range in kriged average total seasonal precipitation for each colored subregion.

Oxnard ◈ **Ventura County Flood Control District precipitation station with selected names**

○ **City or town**

Figure 3—Continued**.** Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***C***, Wet spring.

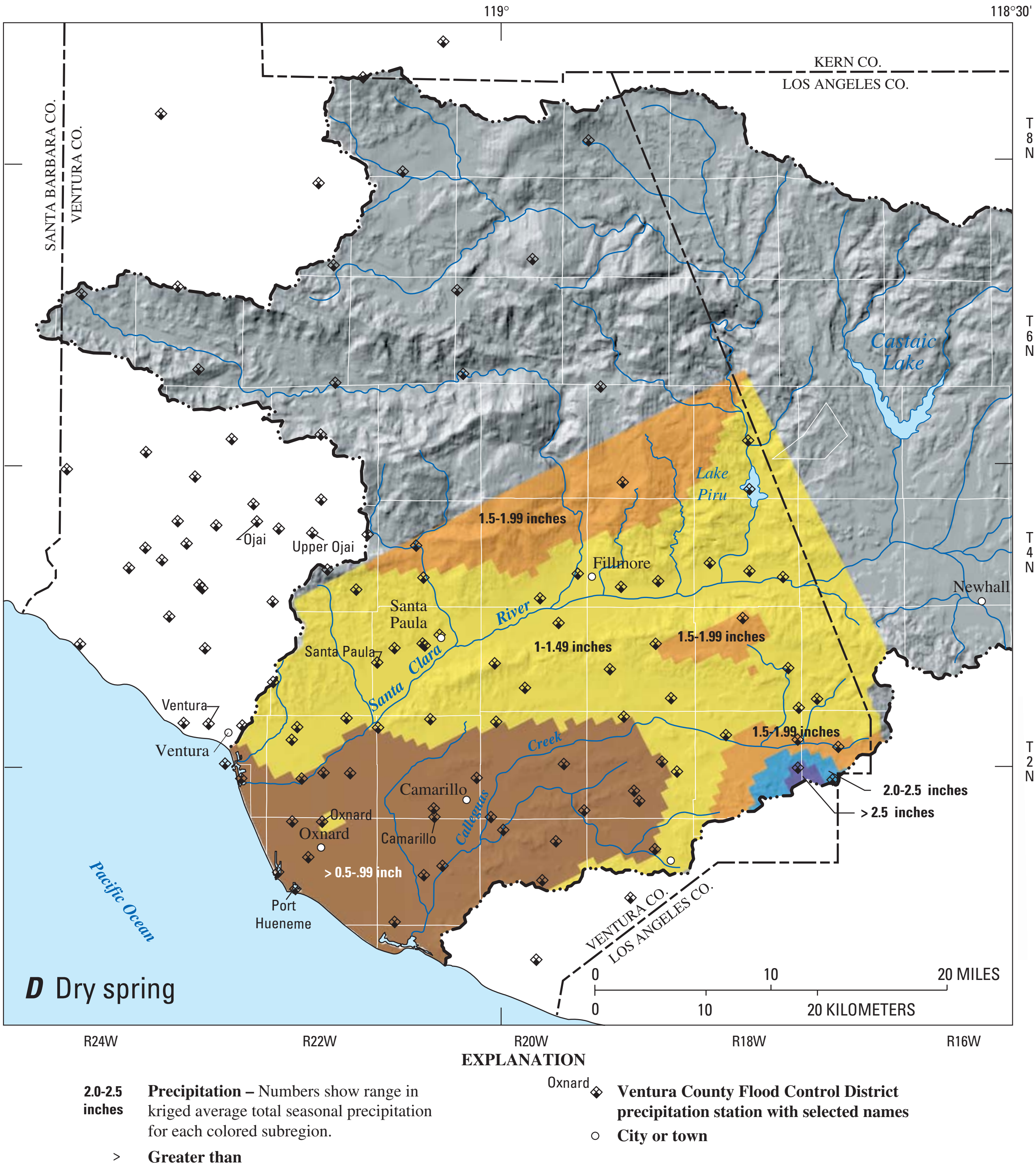
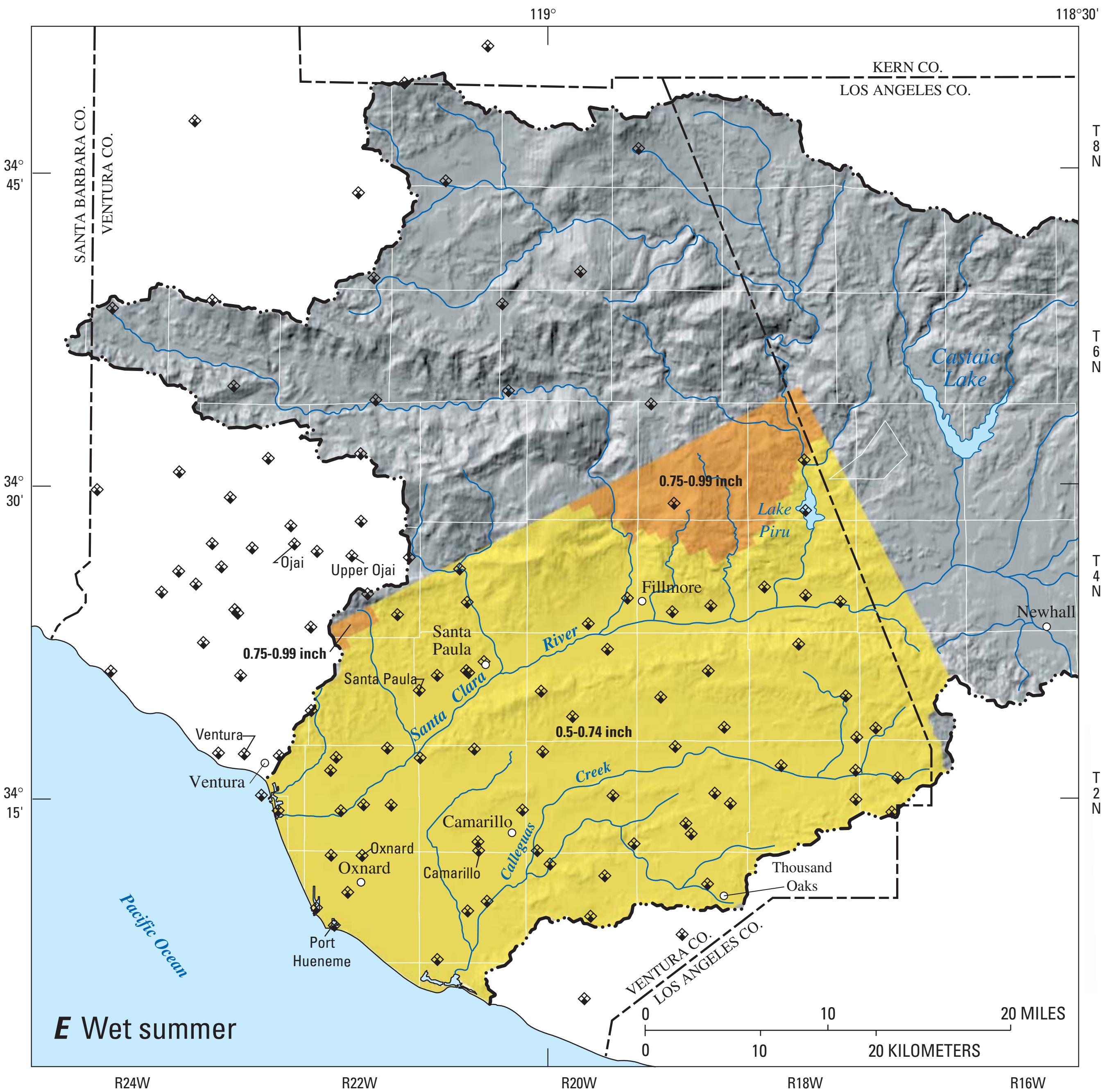


Figure 3—Continued. Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***D***, Dry spring.



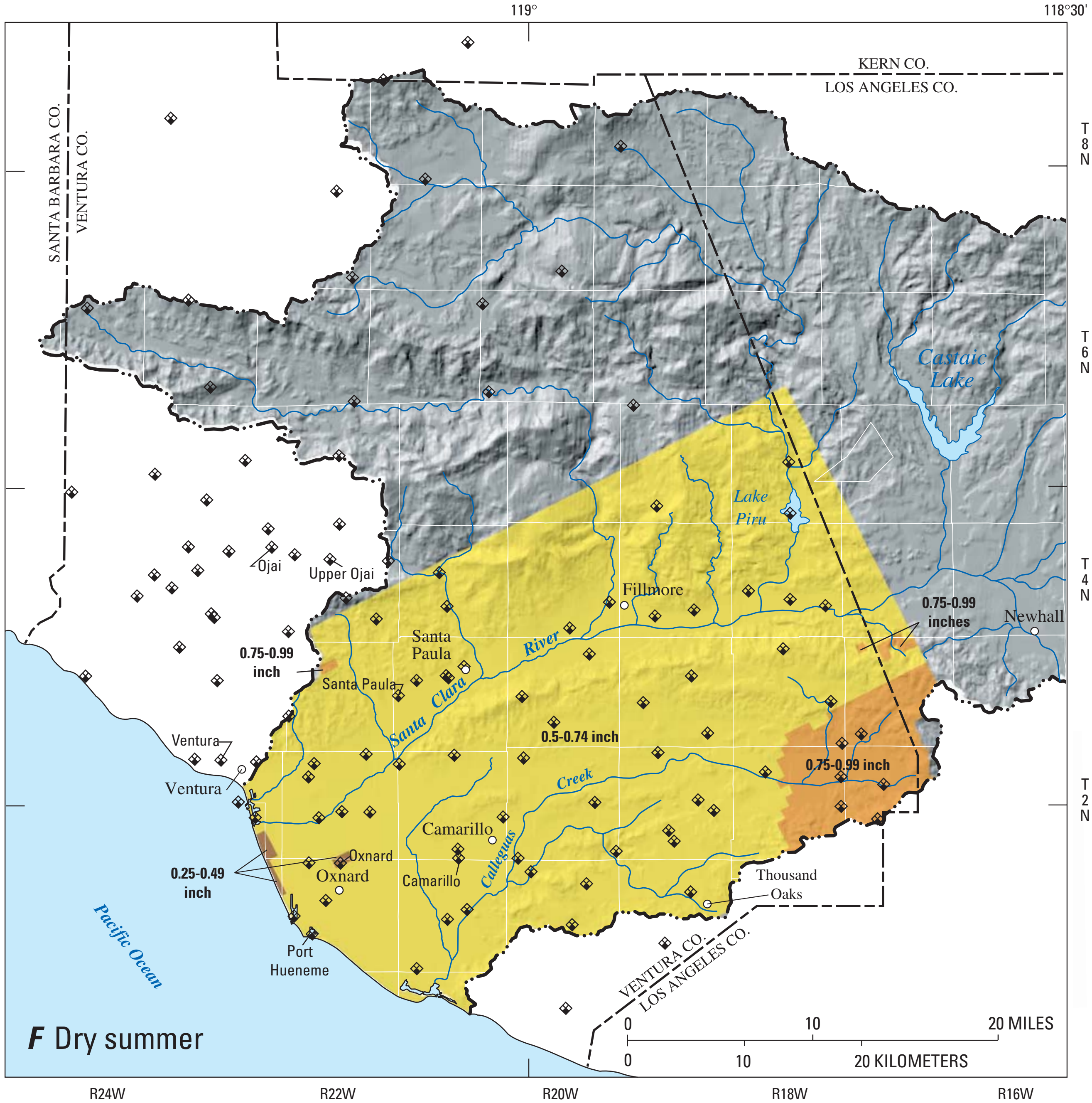
EXPLANATION

0.75-0.99 inches **Precipitation –** Numbers show range in kriged average total seasonal precipitation for each colored subregion.

Oxnard **Ventura County Flood Control District precipitation station with selected names**

City or town

Figure 3—Continued.Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***E***, Wet summer.



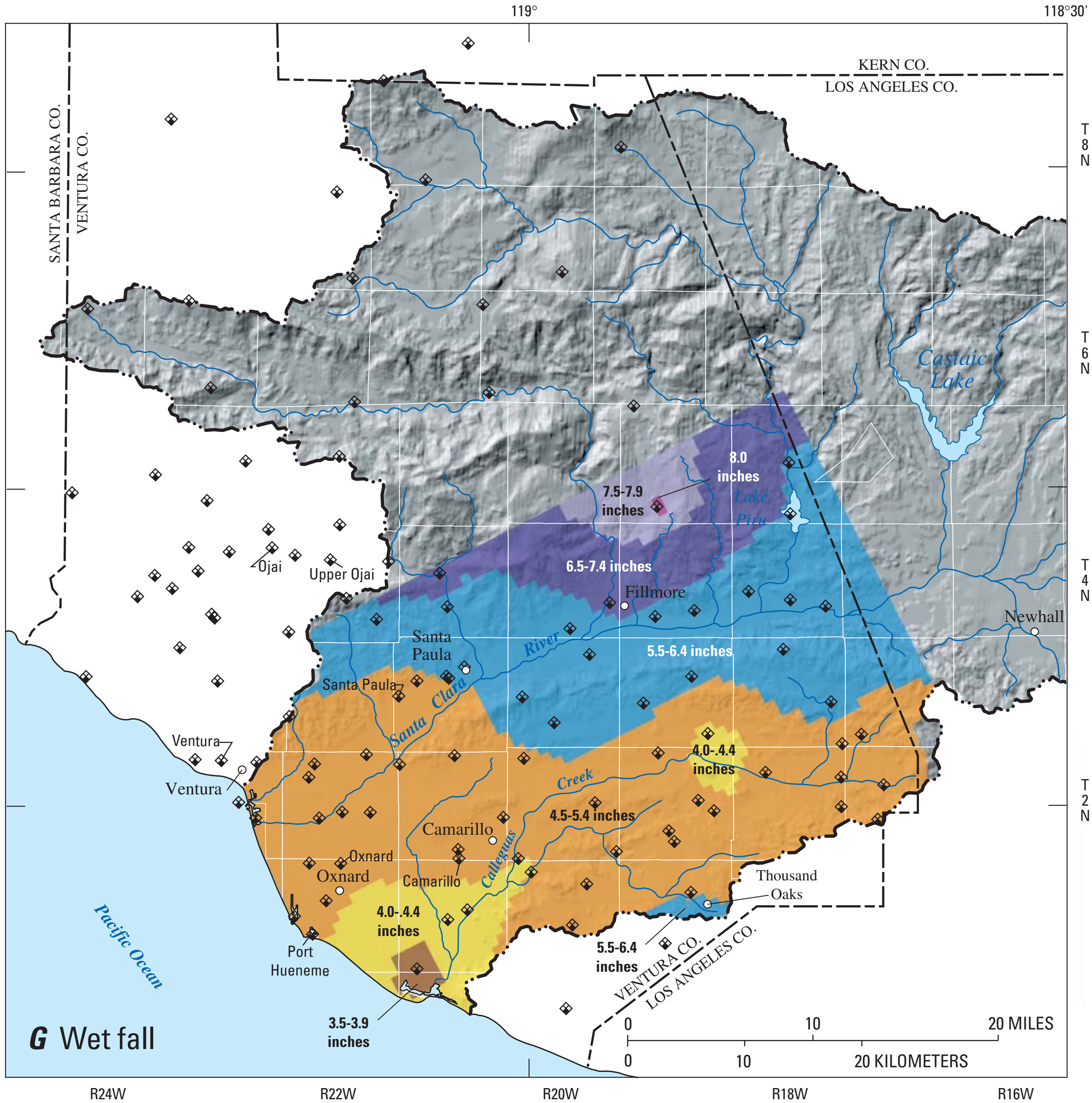
EXPLANATION

0.25-0.49 inches **Precipitation –** Numbers show range in kriged average total seasonal precipitation for each colored subregion.

Oxnard **Ventura County Flood Control District precipitation station with selected names**

City or town

Figure 3—Continued. Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***F***, Dry summer.



EXPLANATION

3.5-3.9 inches **Precipitation –** Numbers show range in kriged average total seasonal precipitation for each colored subregion.

Oxnard ◈ **Ventura County Flood Control District precipitation station with selected names**

○ **City or town**

Figure 3—Continued. Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***G***, Wet fall.

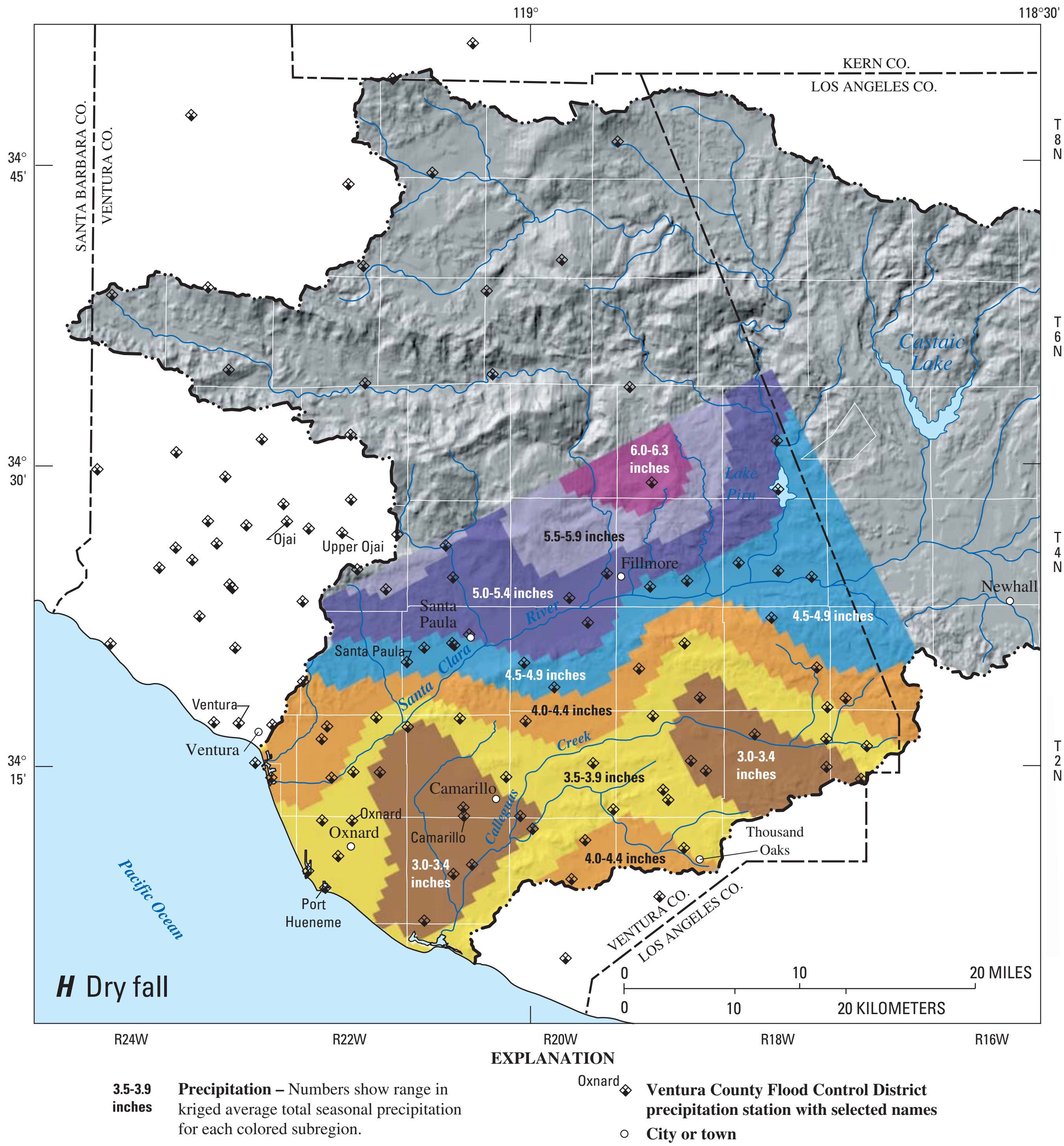


Figure 3—Continued. Kriged average total seasonal precipitation 1891–1991 for wet and dry climatic periods by season. ***H***, Dry fall.

Table 1. Summary of coastal precipitation statistics for the Santa Clara–Calleguas Basin, Ventura County, California

[Data from Ventura County, Department of Public Works (Dolores Taylor, written commun., 1992). Grouping: Dry years represent all years in which precipitation was less than the mean for the period of record; wet years represent all years in which precipitation was more than the mean for the period of record. Dry-year periods are periods of decreasing cumulative departure for precipitation for the period of record and wet-year periods are periods of increasing cumulative departure. W is a value of Shapiro–Wilk Statistic normality test where values close to 1 indicate a significant probability of a normally distributed group of mean total seasonal precipitation.%, percent; —, reference group]

Precipitation period (group number)	Grouping	Mean/standard deviation, in inches (number of samples)	W: Normality test	Significant difference in means at 95-percent level between groups?
Coastal winter (1)	All years	8.37/5.19(101)	0.93	—
Coastal winter (2)	Dry years	5.47/2.48(70)	.97	(1)–(2):Yes (2)–(3): No
Coastal winter (3)	Dry-year periods	6.24/3.28(58)	.93	(1)–(3):Yes
Coastal winter (4)	Wet years	14.93/3.20(31)	.94	(1)–(4):Yes (4)–(5): Yes
Coastal winter (5)	Wet-year periods	11.19/5.85(43)	.96	(1)–(5):Yes
Coastal spring (1)	All years	1.15/1.13(100)	.83	—
Coastal spring (2)	Dry years	.31/.73(70)	.48	(1)–(2):Yes (2)–(3): Yes
Coastal spring (3)	Dry-year periods	1.05/.96(57)	.87	(1)–(3):No
Coastal spring (4)	Wet years	1.03/1.10(30)	.83	(1)–(4):No (4)–(5): No
Coastal spring (5)	Wet-year periods	1.30/1.33(43)	.84	(1)–(5):No
Coastal summer (1)	All years	.30/.66(100)	.53	—
Coastal summer (2)	Dry years	.30/.73(70)	.48	(1)–(2):No (2)–(3): No
Coastal summer (3)	Dry-year periods	.26/.68(57)	.43	(1)–(3):No
Coastal summer (4)	Wet years	.28/.48(30)	.66	(1)–(4):No (4)–(5): No
Coastal summer (5)	Wet-year periods	.36/.65(43)	.64	(1)–(5):No
Coastal fall (1)	All years	4.11/2.74(99)	.94	—
Coastal fall (2)	Dry years	4.01/2.68(69)	.95	(1)–(2):No (2)–(3): No
Coastal fall (3)	Dry-year periods	3.86/2.63(56)	.94	(1)–(3):No
Coastal fall (4)	Wet years	4.33/2.90(30)	.94	(1)–(4):No (4)–(5): No
Coastal fall (5)	Wet-year periods	4.44/2.87(43)	.95	(1)–(5):No

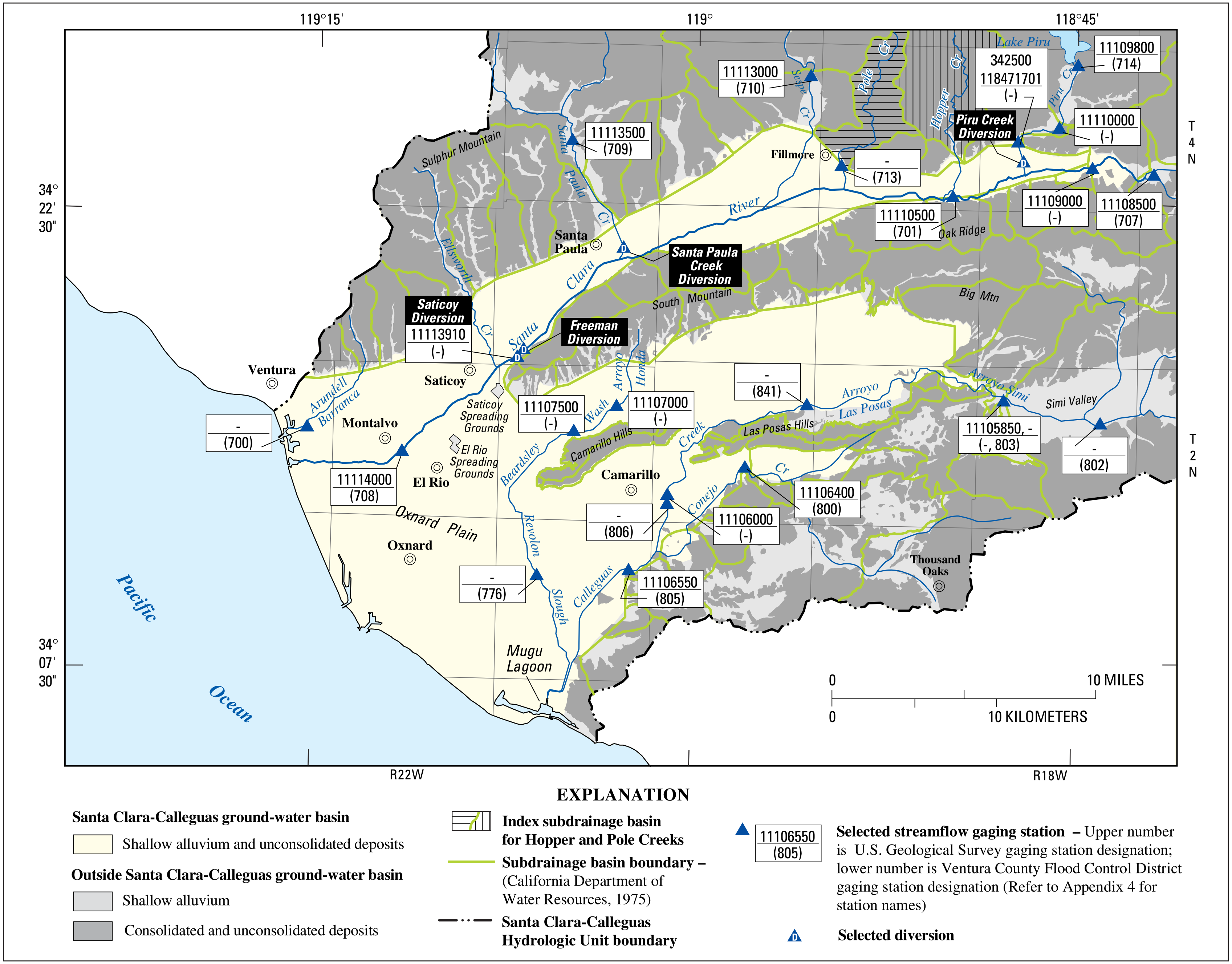


Figure 4. Surface-water drainage features, selected gaging stations, and selected diversions in the Santa Clara–Calleguas ground-water basin, Ventura County, California.

Hydrographs of daily mean streamflow for eight gaging stations in the Santa Clara–Calleguas Basin are presented in figure 5. Natural streamflow in all the major streams and tributaries in the basin is intermittent to ephemeral (fig. 5). Runoff from precipitation primarily during December through April results in natural streamflow in the winter and spring. Most of the streamflow occurs as floodflow. Some of the flows recharge the ground-water system and the remainder discharges into the Pacific Ocean. Sespe Creek is the largest contributor of streamflow to the Santa Clara River system and Piru Creek is the second largest (table 2). Major streams generally have fewer intermittent reaches or become perennial during wet-year periods and have more floodflows and larger baseflows (fig. 5). The Santa Clara River, Piru Creek, Arroyo Simi, and Conejo Creek all have components of regulated flow. The average and median streamflow, and the number of days of flow for the total period of record and for the wet and dry periods defined for this study (fig. 2) are summarized in table 2. These components of regulated flow increased the mean flow and decreased the number of days with no flow (table 2).

Major floods generally occur during wet periods but can occur during dry-year periods (figs. 2 and 5). In 1969, the peak discharge for the largest flood for the period of record was more than 110,000 ft^3/s at the Montalvo gage (11114000) on the Santa Clara River (not shown in figure 5). In the Santa Clara River and most of its major tributaries, multiple-year recession periods generally follow wet periods for unregulated streamflow (fig. 5). During these subsequent years, the gaged outflow at Montalvo can be greater than the gaged inflow of the Santa Clara River and its major tributaries.

Streamflow-duration curves of gaged streams show major differences between wet and dry periods (fig. 6). Streamflow on Piru, Pole, Sespe, and Santa Paula Creeks is perennial during wet years (fig. 6 *C,D,F,G*). The magnitude of daily streamflow increases by a factor of three to five from dry to wet years for streamflows of the same frequency at the seven gaging stations in the Santa Clara–Calleguas ground-water basin (fig. 6 *A–G*).

Since the construction of the Santa Felicia Dam in 1955, controlled releases of water from Lake Piru have resulted in fewer days of no flow in the Santa Clara River; however, average annual streamflow in the river was reduced by 35 percent during the 21-year period (1956–75) after construction of the dam (Taylor and others, 1977). Since 1969, discharge owing to the release of treated wastewater from Los Angeles County and imported water from Castaic Lake has increased the minimum flow in the Santa Clara River across the Los Angeles–Ventura County line from less than 10 ft^3/s to about 20 ft^3/s (fig. 5*A*). In the Calleguas Creek drainage, regulated flow has resulted in additional baseflow owing to discharge of treated municipal sewage along Arroyo Simi and Conejo Creek since about 1970 (fig. 5*B*) and discharge of shallow ground water from dewatering wells. Since 1962, the release of sewage effluent in Conejo Creek has resulted in an increase in baseflow from 0.5 to 15 ft^3/s (fig. 5). The pumping of shallow ground water for dewatering upstream in Simi Valley has resulted in additional baseflow on the Arroyo Simi at the Madera Road Bridge (fig. 5*G*)—an increase from less than 0.1 ft^3/s to about 4 ft^3/s since 1969. Streamflow has become more intermittent on the Santa Clara River at Montalvo since 1929 owing to diversions at Saticoy and Freeman. Based on historical basinwide estimates of streamflow and runoff, ungaged tributary runoff provides the second (California Department of Water Resources, 1975; tables 23 and 24) or third (California Department of Public Works, 1934; table 59) largest contribution to streamflow. Diversion from Sespe Creek, as well as numerous smaller intermittent diversions from the Santa Clara River for irrigation, is still occurring. Diversions from Piru Creek below Santa Felicia Dam and from the Santa Clara River at the Freeman Diversion provide water for artificial recharge. Controlled releases from Lake Piru Reservoir are conveyed down the natural stream channel to these artificial-recharge spreading grounds, supplementing the intermittent natural streamflow during the generally dry summer and fall months.

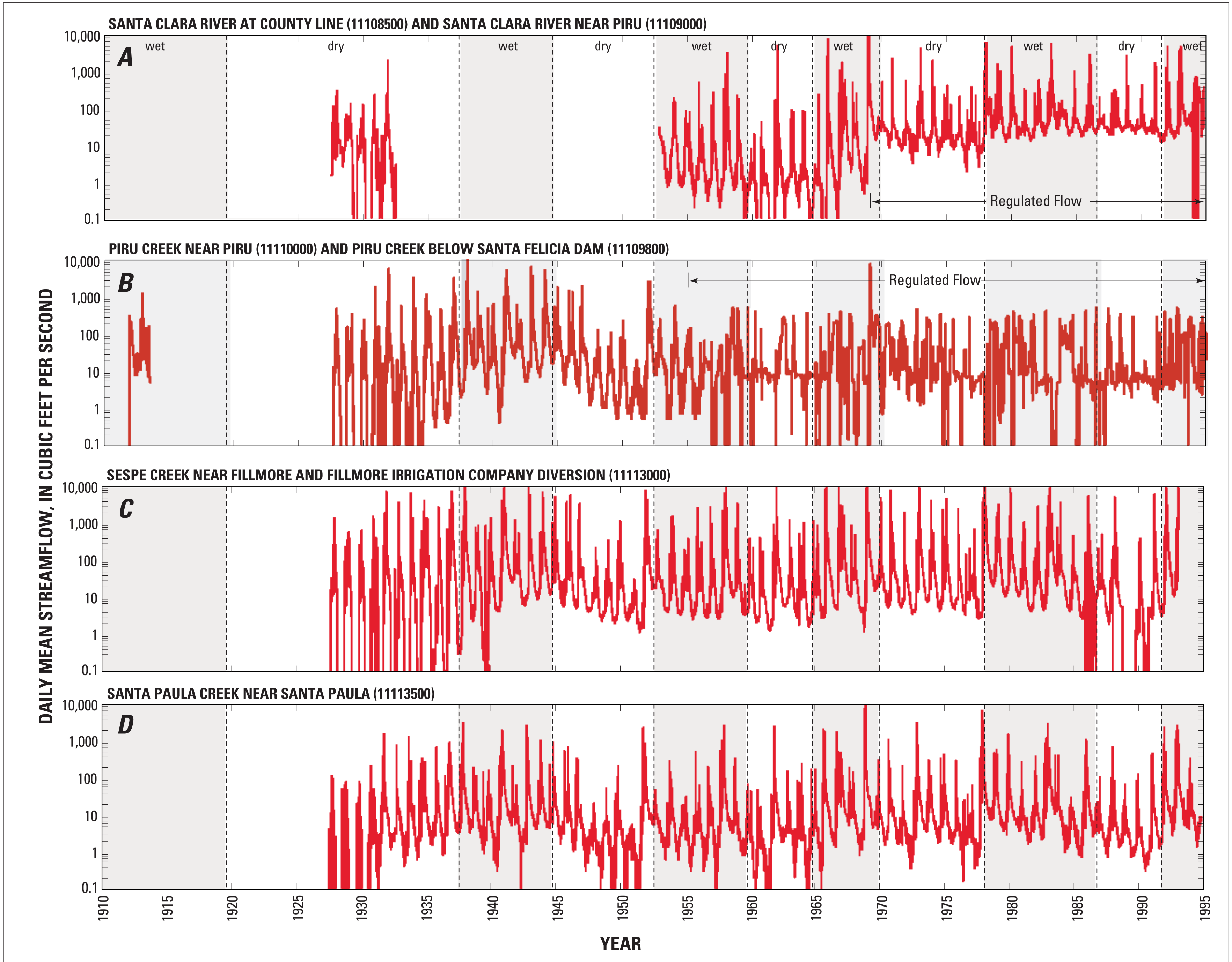


Figure 5. Daily mean streamflow for wet and dry periods at the major rivers and tributaries in the Santa Clara–Calleguas ground-water basin, Ventura County, California.

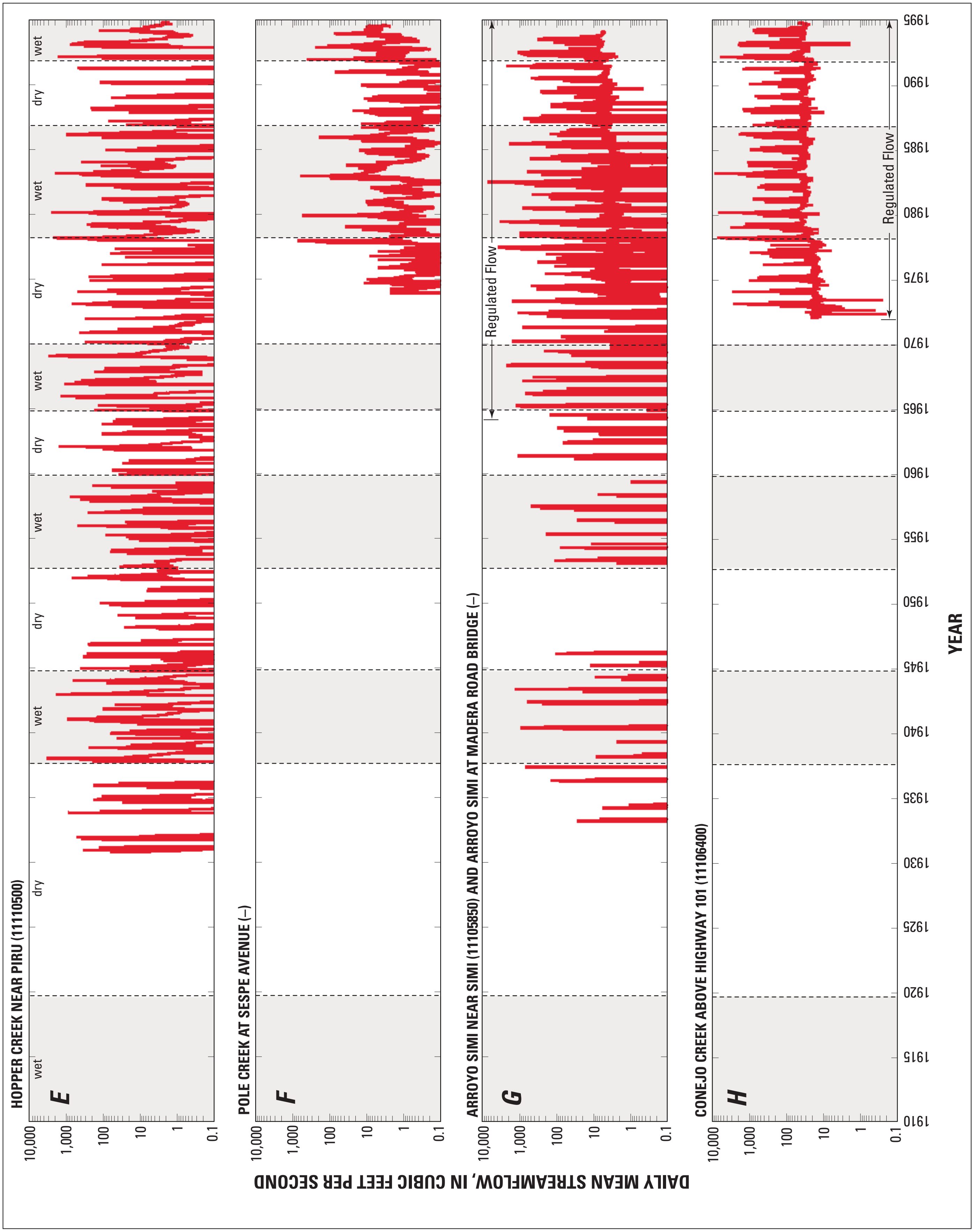


Figure 5—Continued.

Table 2. Summary of gaged streamflow data for selected streams in the Santa Clara–Calleguas Basin, Ventura County, California

[Streamflow gaging station (station number): preceding the slash is the U.S. Geological Survey gaging station number and following the slash is the Ventura County Flood Control District gaging station number. --, no station number provided; —, no estimate provided]

Streamflow gaging station (station No.) [period of record]	Arithmetic average streamflow (cubic feet per second)			Median/geometric mean streamflow (cubic feet per second)			Number of no-flow days			Time averaged streamflow used in predevelopment model (cubic feet per second)
	Total period	Wet periods	Dry periods	Total period	Wet periods	Dry periods	Total period	Wet periods	Dry periods	
Santa Clara River at county line[1] (11108500 / 707) Unregulated flow [1928–32, 1953–71]	32.1	52.5	14.5	2.6/4.3	3.2/4.6	1.9/4.0	801	100	701	2.0
Santa Clara River at county line (11108500 / 707) Regulated and unregulated flow [1953–91][2]	48.3	69.3	26.2	17.0/11.4	20.0/ 13.1	14.0/ 9.7	464	100	364	—
Piru Creek near Piru (11110000 / —) [1912–13, 1927–54]	57.3	100	23.7	12.0/12.8	22.0/23.4	5.1/7.2	1,038	4	1,034	13.0
Piru Creek below Santa Felicia Dam (11109800 / 714) [1956–92]	42.1	54.6	28.7	12.0/12.2	8.7/14.5	7.2/10.3	544	450	94	—
Hopper Creek near Piru (11110500 / 701) [1931–90]	6.2	9.7	2.4	.3/1.1	.7/ 1.6	.01/.6	7,765	2,660	4,032	0.3
Pole Creek at Sespe Avenue, Fillmore (–/ 713) [1974–91]	2.3	3.5	.7	.6/.6	1.0/1.0	.3/.3	25	2	23	0.6
Sespe Creek near Fillmore (11113000 / 710)[3] [1940–91]	125.4	179.8	64.2	17.0/20.7	26.0/30.7	10.0/13.2	0	0	0	18.0
Santa Paula Creek near Santa Paula (11113500 / 709) [1928–91]............	22.5	36.5	10.8	4.5/5.4	7.2/8.7	2.9/3.5	854	0	854	4.5
Santa Clara River at Montalvo (11114000 / 708)[4] [1955–71][5]	222.2	319.8	113.0	25.0/47.9	33.9/71.5	18.2/30.7	1,244	669	575	—
Santa Clara River at Montalvo (11114000 / 708)[4] [1955–92][6]	257.4	385.4	114.2	46.1/59.7	96.0/106.8	24.5/32.2	1,392	671	721	—
Arroyo Simi near Simi (11105850/—)[7] and Arroyo Simi at Royal Avenue (–1/802) [1934–64]............	1.3	2.1	.5	0/.6	0/.8	0/.3	10,282	4,801	5,481	0
Arroyo Simi near Simi (11105850/--)[7] and Arroyo Simi at Royal Avenue (–/802) [1934–69]	2.3	3.7	.5	0/.9	0/1.5	0/.3	11,942	6,461	5,481	0

[1]Streamflow data combined with streamflow data from Santa Clara River near Piru (11109000) for period 1927–32. Numbers represent the period without wastewater flowing into the basin along the Santa Clara River from Los Angeles County for climate periods.

[2]Values are for the periods with and without wastewater flowing into the basin along the Santa Clara River from Los Angeles County.

[3]Streamflow data was combined with streamflow data from Fillmore Irrigation Canal diversion (11113001/—) for period 1940–91.

[4]Streamflow data was combined with streamflow data from Santa Clara River Diversion at Saticoy (11113910/—) for period 1928–92. Values also represent the period with releases from Lake Piru.

[5]Values represent the period without wastewater flowing into the basin along the Santa Clara River from Los Angeles County.

[6]Values represent the period with and without wastewater flowing into the basin along the Santa Clara River from Los Angeles County, respectively. Values also represent the period with releases from Lake Piru.

[7]Values represent the period without dewatering pumpage flowing into the basin along Arroyo Simi.

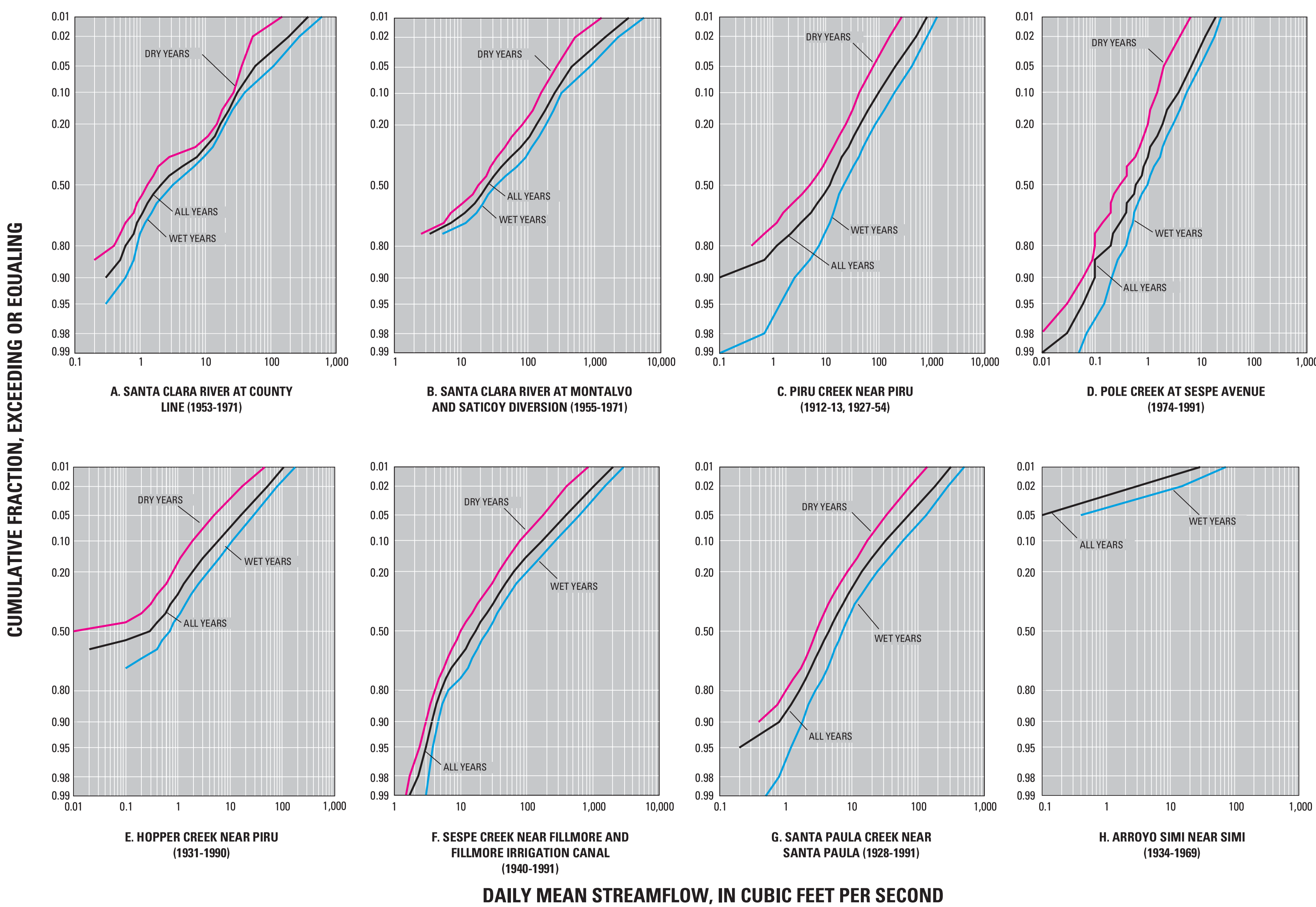


Figure 6. Streamflow duration during wet and dry periods at the major rivers and tributaries in the Santa Clara–Calleguas ground-water basin, Ventura County, California. (See table 2 for gaging station numbers and figure for gaging station locations.)

Irrigation Diversions

Diversion of natural streamflow (fig. 4) was the first water-resources development for agricultural use in the Santa Clara–Calleguas ground-water basin. Major diversions from the Santa Clara River and its tributaries were constructed in the middle to late 1800s. The continued growth of agriculture resulted in irrigation and return-flow diversions in the early 1900s that captured most of nonflood flows from the Santa Clara River. The diversions on the tributaries generally were small, permanent structures on bedrock designed to capture the low perennial baseflows (less than 1 to 10 ft^3/s) during summer and fall. Mainstem diversions, however, commonly were temporary structures that were rebuilt within the shifting channel after the recession of floodflows. Other historically larger diversion canals (not shown on figure 4), such as Farmers Ditch, Santa Clara Water and Irrigation Company Canal, Camulos Ranch Ditch on the Santa Clara River, and Fillmore Land and Water Company Canal on Sespe Creek, conveyed diversions of 10 to 40 ft^3/s [shown in Adams (1913, pl. XVI), and Predmore and others (1997)]. Most of these diversions operated within the subbasins and supplied irrigation water to crops on the adjacent flood plain. The larger mainstem diversions typically were located where there was sustained flow, which generally occurs below the confluence with major tributaries where natural sediment deposited by inflow causes riffles and ponding of streamflow. Some of the mainstem diversions along the Santa Clara River were built near the upstream side of the constrictions at the subbasin boundaries where there is a mixture of streamflow and ground-water discharge. The diversions of surface water supplied a significant amount of the water used for irrigation prior to the early 1930s when irrigation demand exceeded the surface-water supplies largely owing to the 1923–36 drought.

Imported water

Since 1971, surface water has been imported from northern California and routed through a series of reservoirs constructed by the UWCD for controlled release during the growing season. Water from northern California is imported by the UWCD to Pyramid Lake and Lake Piru where it periodically is released into Piru Creek and the Santa Clara River channels. Water has been imported to Castaic Lake since the 1970s where it is released into the Santa Clara River channel. This imported water, along with treated sewage effluent from Los Angeles County, increases the perennial baseflow at the streamflow-gaging station on the Santa Clara River at the Los Angeles–Ventura County Line (fig. 5*A*). Most of the water brought into the basin since 1964 was imported by the CMWD using Metropolitan Water District (MWD) pipelines—about 1,863,000 acre-ft of water from 1964 through 1993. The water was used primarily for municipal supplies (91 percent), and a small part (9 percent) was used for irrigation. Some of this water may have entered the ground-water flow system as sewage-effluent discharge or as percolation of excess applied irrigation water (hereinafter referred to as irrigation return flow) in the Las Posas Valley and Pleasant Valley subbasins. Even though most of the water imported by the CMWD that is used for municipal supply becomes treated sewage effluent that is discharged to the Pacific Ocean, this imported water has helped reduce growth in ground-water pumping in the Oxnard Plain, Pleasant Valley, and Las Posas Valley subbasins.

Sewage Effluent

Sewage effluent is discharged directly to the Pacific Ocean, the Santa Clara River, Calleguas Creek, and Conejo Creek and to percolation ponds for direct infiltration or it was reused for irrigation. Most of the sewage effluent is either directly discharged to the Pacific Ocean or is discharged to stream channels in the Oxnard Plain, where low-permeability channels do not allow significant infiltration to the regional ground-water flow system. Treated sewage effluent is included in the streamflow that enters the basin at the county line along the Santa Clara River, Calleguas River, and Conejo Creek. These contributions to streamflow are part of the gaged streamflow on these rivers.