GROUND WATER

The Santa Clara–Calleguas drainage basin is part of the tectonically active Transverse Ranges physiographic province. The mountains are composed of a variety of consolidated marine and terrestrial sedimentary and volcanic rocks of Late Cretaceous through Quaternary age. The subbasins of the Santa Clara–Calleguas Basin are filled with a mixture of consolidated and unconsolidated marine and terrestrial coastal deposits of Tertiary and Quaternary age. These basin-fill sediments and consolidated rocks form a complex set of aquifer systems that have been the primary source of water supplies since the early 1900s. Agriculture has been the main user of ground water, and in recent years public supply and industry have become significant users of ground water. The geohydrology of the basin is discussed in detail in reports by California Department of Public Works (1934), California Department of Water Resources (1954, 1958, 1974a,b, and 1975), California State Water Resources Board (1956), Mann and Associates (1959), and Turner (1975). The reader is referred to these reports for a more complete description of the geohydrology of the Santa Clara–Calleguas Basin.

Geologic Framework

For this report, the lithologic units mapped by Webber and others (1976), Dibblee (1988, 1990a,b, 1991, 1992a,b,c,d), and Dibblee and Ehrenspeck (1990) in the Santa Clara–Calleguas Basin and surrounding area were grouped into two general categories: (1) upper Cretaceous and Tertiary bedrock, and (2) Quaternary unconsolidated deposits. The outcrop pattern of these combined units is shown in figure 7*A* and their stratigraphic relations are shown in figure 7*B*.

Consolidated Rocks

The upper Cretaceous and Tertiary consolidated rocks include sedimentary, volcanic, igneous, and metamorphic rocks. These rocks are virtually non-water bearing and form the base of the Santa Clara–Calleguas Basin. Although these rocks are not an important source of ground water, the erosion and subsequent deposition of these rocks are the source of the unconsolidated deposits that form the Santa Clara–Calleguas ground-water basin. The sedimentary rocks of Cretaceous age are exposed in the Topatopa Mountains north of the ground-water basin and in the Simi Hills and Santa Susana Mountains south of the basin (California State Water Resources Board, 1956, pl. 10). These rocks are generally non-water bearing except within the poorly cemented and fractured sandstones in the hills near Simi Valley (Turner, 1975, p. 3).

The consolidated Tertiary sedimentary rocks underlie most of the ground-water basin and compose the surrounding mountains and hills. These rocks are predominantly marine in origin and are nearly impermeable except for the slightly permeable sandstones and within fracture zones. Some of these Miocene formations contain oil and tar sand beds, natural gas, and related methane and brines. The Pico Sandstone of Pliocene and Pleistocene epochs underlies the unconsolidated deposits throughout most of the ground-water basin and crops out in the mountains on the north side of the Santa Clara River Valley (California State Water Resources Board, 1956, pl. 10). These rocks are also considered to be of low permeability and non-water bearing.

Volcanic rocks and related intrusive rocks of Miocene age underlie parts of the southern Oxnard Plain, South Pleasant Valley, and Santa Rosa Valley subbasins (figs. 7 and 8*D*,*E*). Although these rocks are considered non-water bearing, they have been developed for water supply where alluvial deposits are absent, such as in the Santa Rosa Valley subbasin. These volcanic and intrusive rocks also crop out in the Santa Monica Mountains along the southern and southeastern boundaries of the ground-water basin (California State Water Resources Board, 1956, pl. 10) and in the offshore submarine canyons along the southwestern boundary of the basin (Kennedy and others, 1987, pl. 2A).

Unconsolidated Deposits

The Quaternary unconsolidated deposits consist of the Santa Barbara Formation (Weber and others, 1976), the Las Posas Sand (Dibblee, 1988, 1990a,b, 1991, 1992a,b,c,d; Dibblee and Ehrenspeck, 1990), the San Pedro Formation (Weber and others, 1976), and the Saugus Formation (Weber and others, 1976; Dibblee, 1988, 1990a,b, 1991, 1992 a,b,c,d), all of the Pleistocene epoch, and unconsolidated alluvial and fluvial deposits of the Pleistocene to Holocene epoch. In the Santa Clara–Calleguas Basin, the unconsolidated deposits are grouped together into the upper-aquifer system and the lower-aquifer system (fig. 7*B*).

The Santa Barbara Formation, mapped by Weber and others (1976), overlies consolidated Tertiary rocks in most of the ground-water basin and consists of marine sandstone, siltstone, mudstone, and shale. The thickness and lithology of the formation varies considerably throughout the basin, but the formation is thickest, more than 5,000 ft, in the Ventura area (Yerkes and others, 1987). The formation is of low permeability and generally contains water of poor quality throughout most of the basin (Turner, 1975) and, therefore, is not considered an important source of ground water. In the East Las Posas Valley subbasin, the Santa Barbara Formation contains layers of sands and gravels that are an important source of water to wells in areas where younger unconsolidated deposits are absent or are unsaturated. The coarse-grained section of the Santa Barbara Formation in the East Las Posas Valley subbasin is commonly referred to as the "Grimes Canyon" member (California Department of Water Resources, 1956).

The Santa Barbara Formation and the lower part of the San Pedro Formation mapped by Weber and others (1976) consist of shallow marine sand and gravel beds that were indicated as a separate formation, the Las Posas Sand, by Dibblee (1988, 1990a,b, 1991, 1992a,b,c,d) and Dibblee and Ehrenspeck (1990). These deposits reach a maximum thickness of more than 2,000 ft in the Santa Clara River Valley near Ventura (Dibblee, 1992a,b,c,d) and consist of a series of relatively uniform fine-grained sand layers 100 to 300 ft thick separated by silt and clay layers 10 to 20 ft thick. The upper part of San Pedro Formation consists of lenticular layers of sand, gravel, silt, and clay of marine and continental origin. The continental fluvial silt, sand, and gravel deposits within the upper part of the San Pedro Formation are referred to as the Saugus Formation by Dibblee (1988, 1990a,b, 1991, 1992a,b,c,d) and Dibblee and Ehrenspeck (1990). These deposits reach a maximum thickness of more than 5,000 ft in the Piru subbasin in the Santa Clara River Valley (Dibblee, 1991). The sand and gravel layers range from 10 to 100 ft thick and are separated by silt and clay layers that generally are 10 to 20 ft thick. The Santa Barbara and San Pedro Formations are absent in the Santa Rosa Valley subbasin east of the San Pedro Fault and in the South Pleasant Valley subbasin southeast of the Bailey Fault. In the eastern part of the Santa Rosa Valley subbasin and in the eastern part of the South Pleasant Valley subbasin, recent alluvial and terrace deposits were deposited unconformably on the marine shale and sandstone beds of the Santa Margarita Formation (Late Miocene) or rest unconformably on the Conejo Volcanics (Middle Miocene). For this study, the Santa Margarita Formation in the Santa Rosa Valley subbasin is grouped with the unconsolidated sediments of the lower system. During the Pleistocene epoch, major changes in sea level resulted in cycles of erosion and deposition (Dahlen, 1992). The sequence of deposits above the erosional unconformities typically starts with a basal conglomerate that is laterally extensive, relatively more permeable than the underlying deposits, and a potential major source of water to wells perforated in these deposits. These coarse-grained layers of fluvial and beach deposits are interbedded with extensive fine-grained layers.

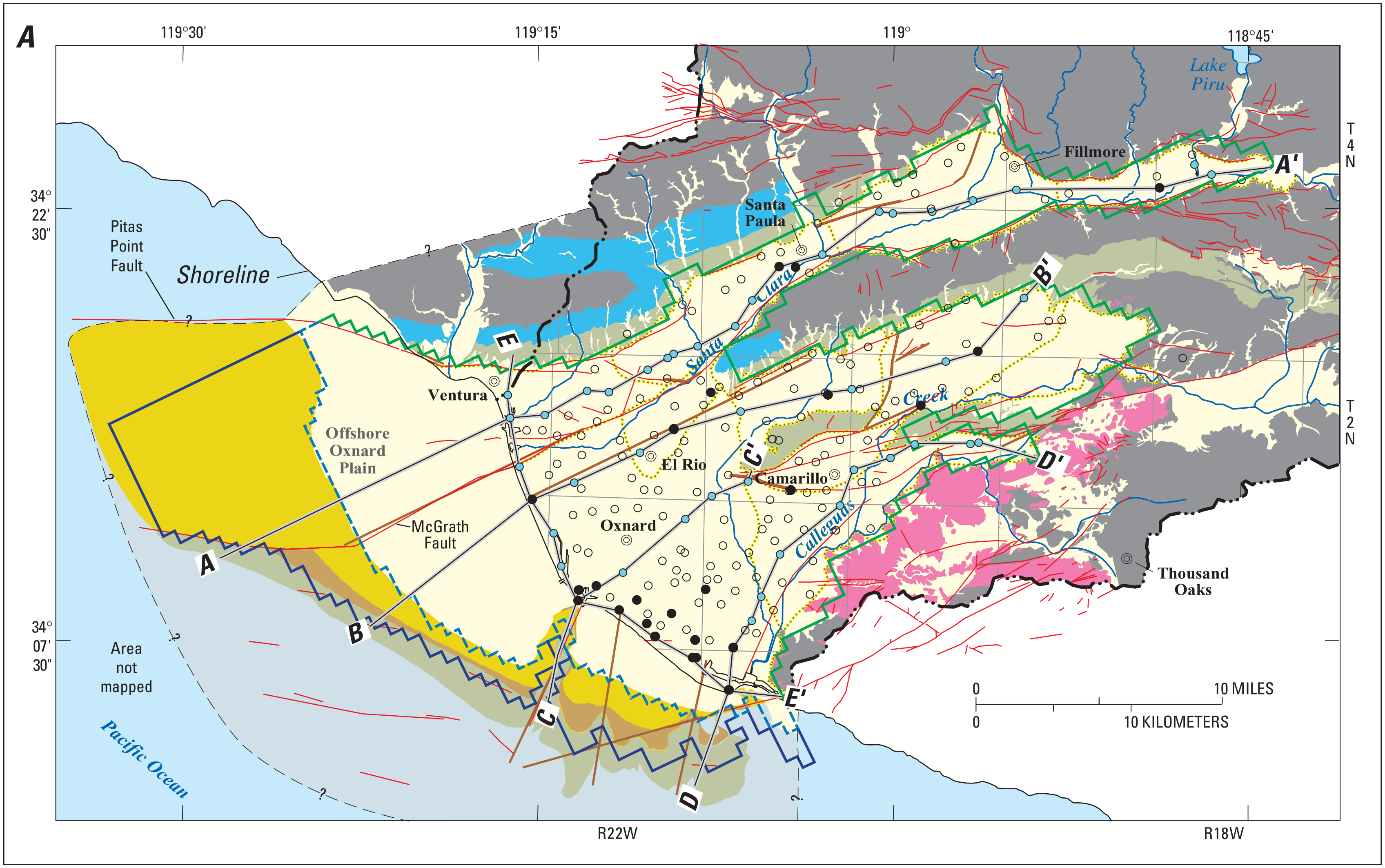


Figure 7. ***A,*** Generalized surficial geology of the Santa Clara–Calleguas ground-water basin and extents of layers in the numerical ground-water flow model, and ***B***, stratigraphic column and related aquifer designations of geologic units by source and aquifer-system model layers, Ventura County, California. (Modified from Weber and others, 1976).

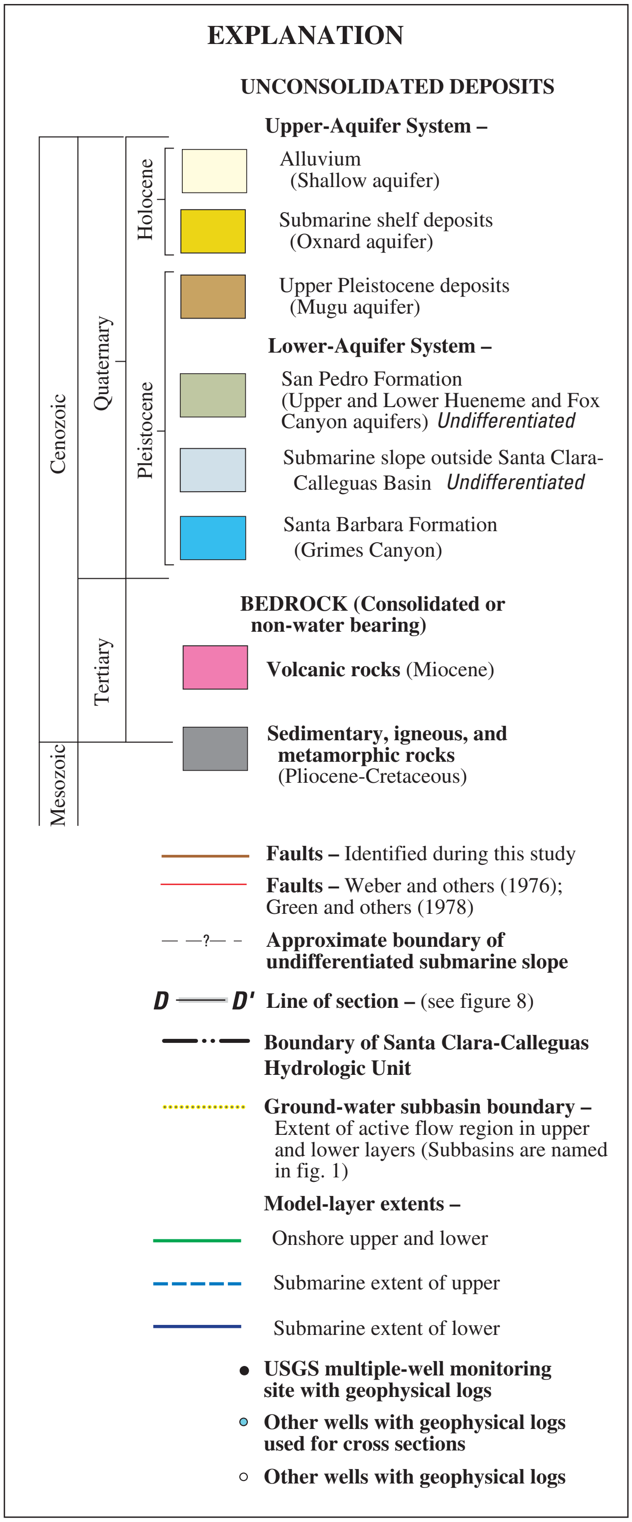


Figure 7—Continued.

The Late Pleistocene and Holocene deposits are unnamed, consist of relatively flat-lying marine and continental unconsolidated deposits, and are regionally grouped into the upper system of water-bearing deposits (fig. 7*B*). These deposits, which were derived from local sources and from the Santa Clara River and Calleguas Creek, were deposited unconformably on the older unconsolidated deposits and contain basal conglomerates that are laterally extensive and produce substantial ground-water supplies. In the Mound and Oxnard Plain subbasins, the basal zones are overlain with fine-grained deposits of low permeability. Alluvial and fluvial sand and gravel deposits with interbedded fine-grained deposits of the Holocene epoch unconformably overlie the Late Pleistocene deposits. The basal deposits of the Holocene epoch consist of gravel and sand, which are overlain by fine-grained deposits throughout most of the Santa Clara River Valley and Oxnard Plain subbasins. These basal deposits are relatively more permeable than underlying deposits, and are potential major sources of water to wells completed in the saturated parts of these deposits. Interbedded sand layers occur within the fine-grained deposits throughout most of the Oxnard Plain. With the exception of recent coarse-grained channel deposits along the Santa Clara River and Calleguas Creek, the thin layer of Holocene deposits that are not coincident with minor tributaries are relatively fine grained and relatively low in permeability.

Figure 7B. Stratigraphic column and related aquifer designations of geologic units by source and aquifer system model layers in the ground-water and surface-water flow model of the Santa Clara–Calleguas Basin, Ventura County, California—Continued

Geologic era	Geologic system	Geologic series (epoch)	Weber and others (1976)	Dibblee[1]	Turner (1975) Green and others (1978)[2]	RASA[3]	Aquifer system model layers
			Lithologic units and Formations		Aquifers		
Cenozoic	Quaternary	Holocene	***Recent Alluvium*** (Lagoonal, beach, river and flood plain deposits, artificial fill, and alluvial fan deposits)		Recent alluvial and semiperched	Shallow	Upper-aquifer system[4], layer 1
			Recent Alluvium (Lagoonal, beach, river and flood plain deposits and alluvial fan deposits)		Oxnard[5]		
		Late (Upper) Pleistocene[6]	***Older Alluvium*** (Lagoonal, beach, river and flood plain, alluvial fan, terrace, and marine terrace deposits)		Mugu[2]		
			Saugus Formation[7] (Terrestrial fluvial sediments)	Saugus Formation	Hueneme	Upper Hueneme	Lower-aquifer system, layer 2
			San Pedro Formation[8] (Marine clays and sands and terrestrial fluvial sediments)			Lower Hueneme	
				Las Posas Sand (Marine shallow regressive sands)	Fox Canyon	Fox Canyon	
		Early (Lower) Pleistocene[6]	***Santa Barbara Formation***[8] (Marine shallow regressive sands)		Grimes Canyon[9,10]	Grimes Canyon	
			Pico Formation [11] (Marine siltstones, sandstones, and conglomerates)		Formation not included in regional flow model		Formation not included in regional flow model
	Tertiary	Pliocene[6]	***Repetto formation*** (Terrestrial conglomerates, sandstones, and shales)				
		Miocene	***Santa Margarita Formation, Monterey Shale, Rincon Mudstone, Towsley Formation*** (Terrestrial fluvial sandstones and fine-grained lake deposits)		Not Included	Santa Margarita sandstones included in northeastern Santa Rosa Valley	Lower-aquifer system, layer 2
			Conejo Volcanics (Terrestrial and marine extrusive and intrusive, felsic-andesites to basalts)		Formation not included in regional flow model		Formation not included in regional flow model
			Lower Topanga Formation, Topanga-Vaqueros Sandstones, Modelo Formation, Sisquoc Formation (Marine transgressive sands and siltstones)				
		Oligocene	***Sespe Formation*** (Terrestrial fluvial claystones and sandstones)				
		Eocene	***Llajas Formation, Coldwater Sandstone, Cozy Dell Shale, Matilija Sandstone, Juncal Formation, Santa Susana Formation*** (Marine sandstones, mudstones, and claystones)				
		Paleocene	***Martinez Formation*** (Terrestrial conglomerate, sandstones, and marine shales)				
Mesozoic	Upper Cretaceous		Chico Formation (Sandstones with shales)				

Figure 7B. Stratigraphic column and related aquifer designations of geologic units by source and aquifer system model layers in the ground-water and surface-water flow model of the Santa Clara–Calleguas Basin, Ventura County, California—Continued

[1]Formations from Dibblee (1988; 1990a,b; 1991; 1992a,b,c,d) and Dibblee and Ehrenspeck (1990).
[2]Perched aquifer designated in parts of the Oxnard Plain only.
[3]From the current study as part of the Southern California Regional Aquifer-System Analysis Program of the U.S. Geological Survey.
[4]Shallow aquifer included in the Oxnard Plain Forebay and inland subbasins. Semiperched part of Shallow aquifer not included in remainder of Oxnard Plain.
[5]Restricted to the Oxnard Plain and Forebay by Turner (1975).
[6]Modified on the basis of ash-deposit age dates (Yerkes and others, 1987, fig.11.2).
[7]Mapped in eastern Ventura County subbasins of Santa Paula, Fillmore, Piru, and Las Posas Valley and may be time equivalent to parts of the San Pedro and Santa Barbara Formations (Weber and others, 1976, fig. 3).
[8]Mapped in western Ventura County subbasins.
[9]San Pedro Formation everywhere except in Pleasant Valley where the Santa Barbara Formation was assigned to the Grimes Aquifer.
[10]Las Posas and Pleasant Valley subbasins only.
[11]Includes Mud Pit and Claystone Members.

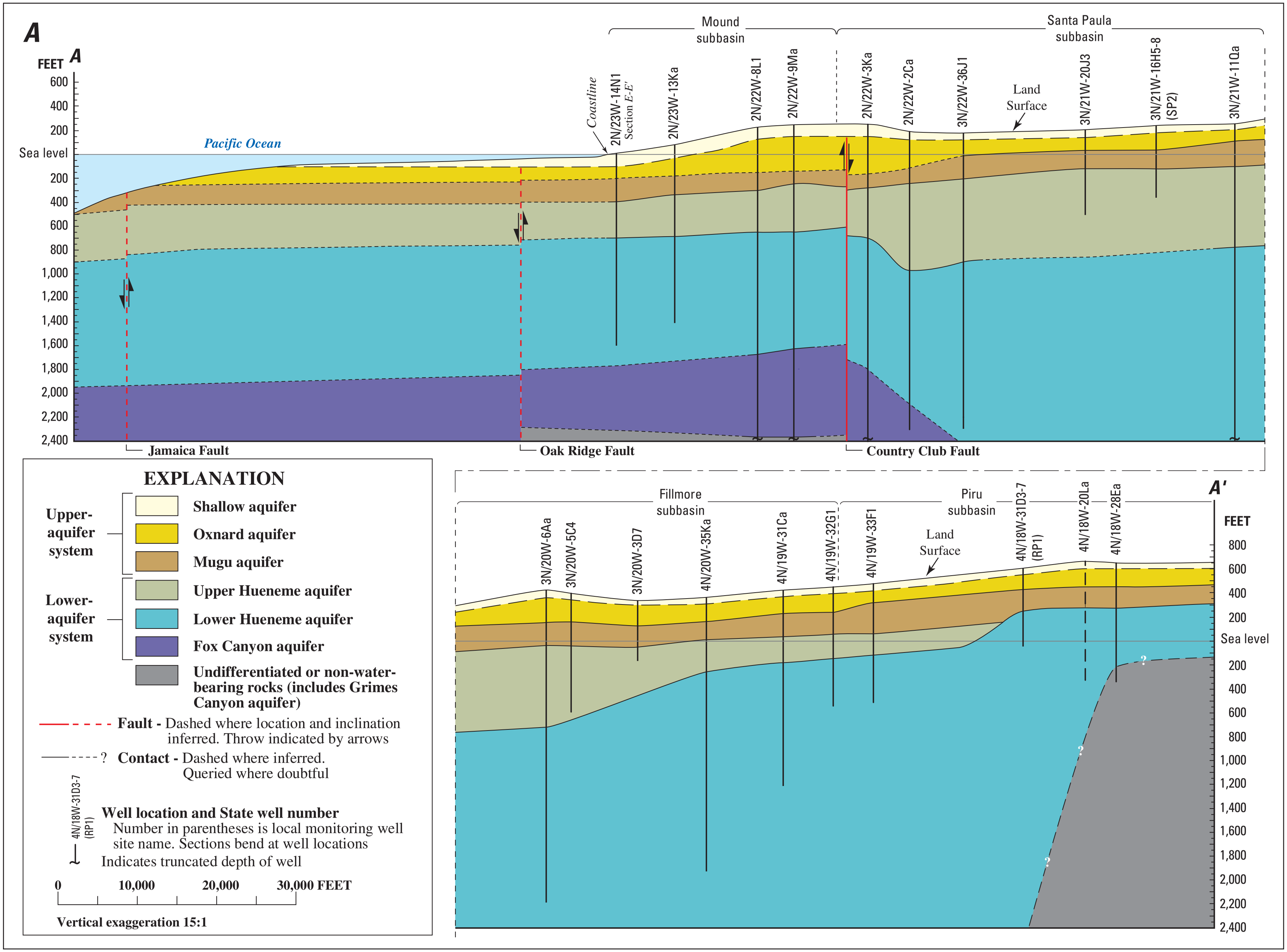
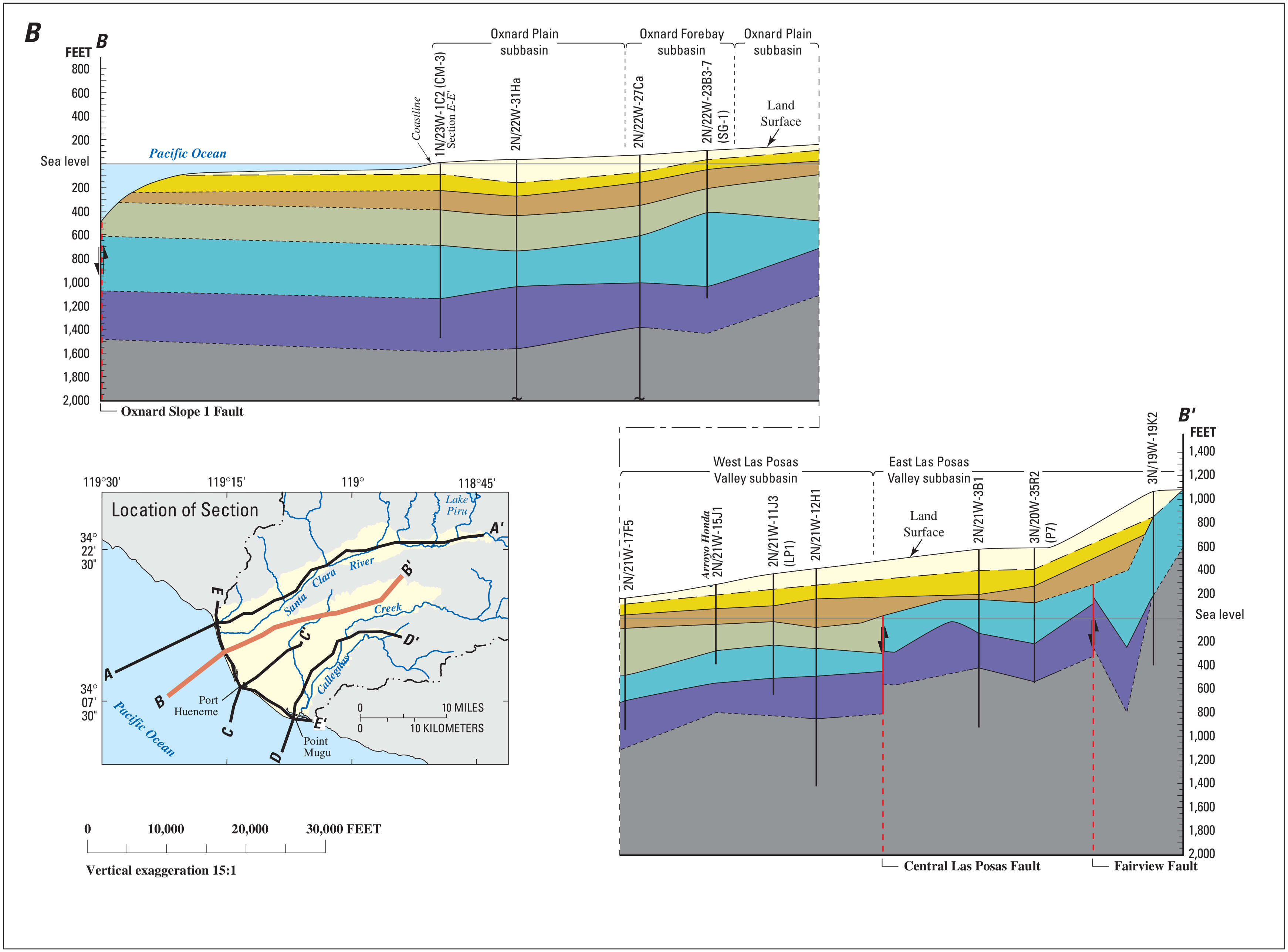


Figure 8. Hydrogeology of the Santa Clara–Calleguas ground-water basin, Ventura County, California. ***A***, Section *A–A′* Santa Clara River. ***B***, Section *B–B′*, Los Posas. ***C***, Section *C–C′*, Hueneme. ***D***, Section *D–D′*, Pleasant Valley. ***E***, Section *E–E′*, Coastal. (See figure 7*A* for location of sections.)



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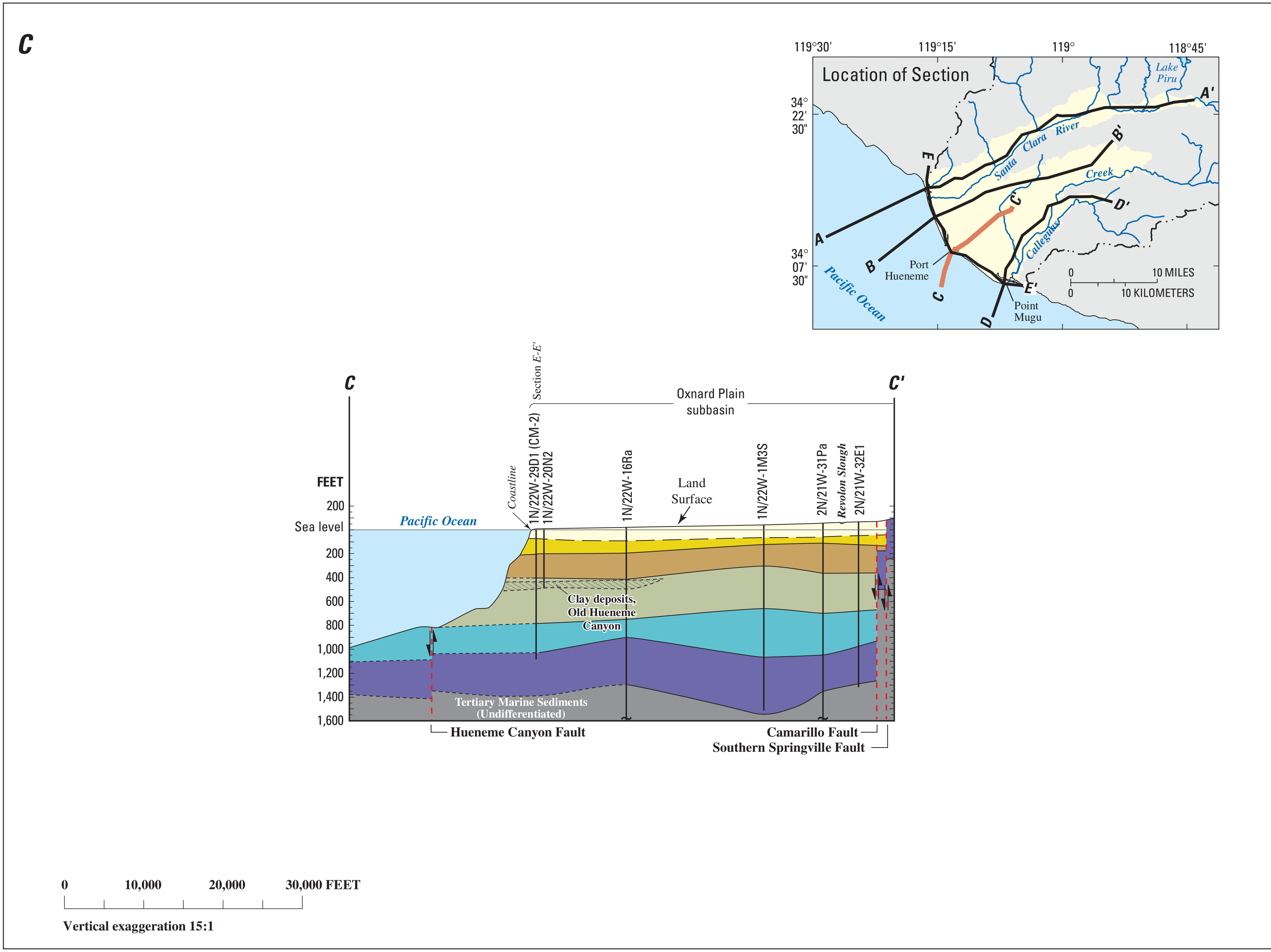

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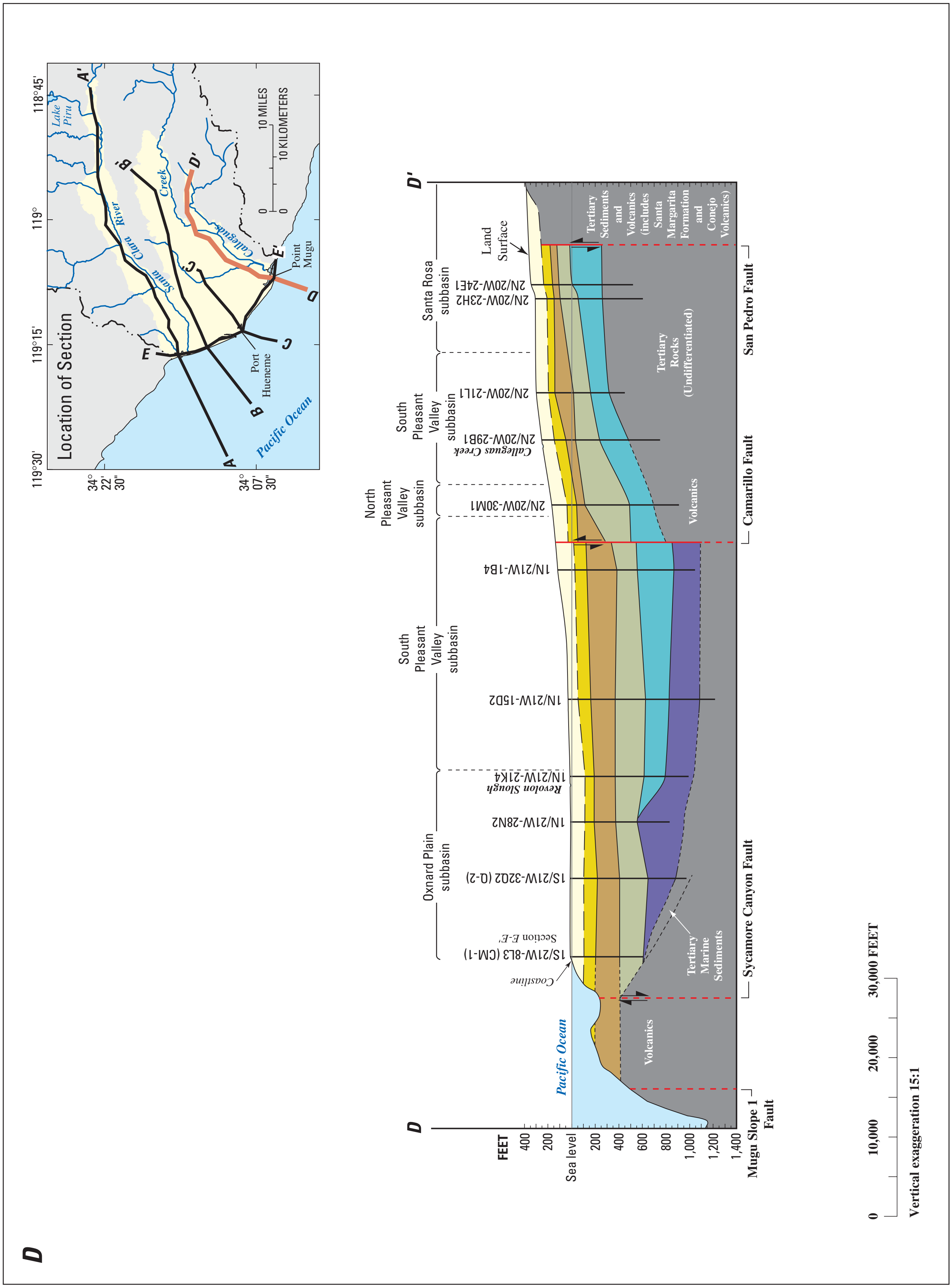

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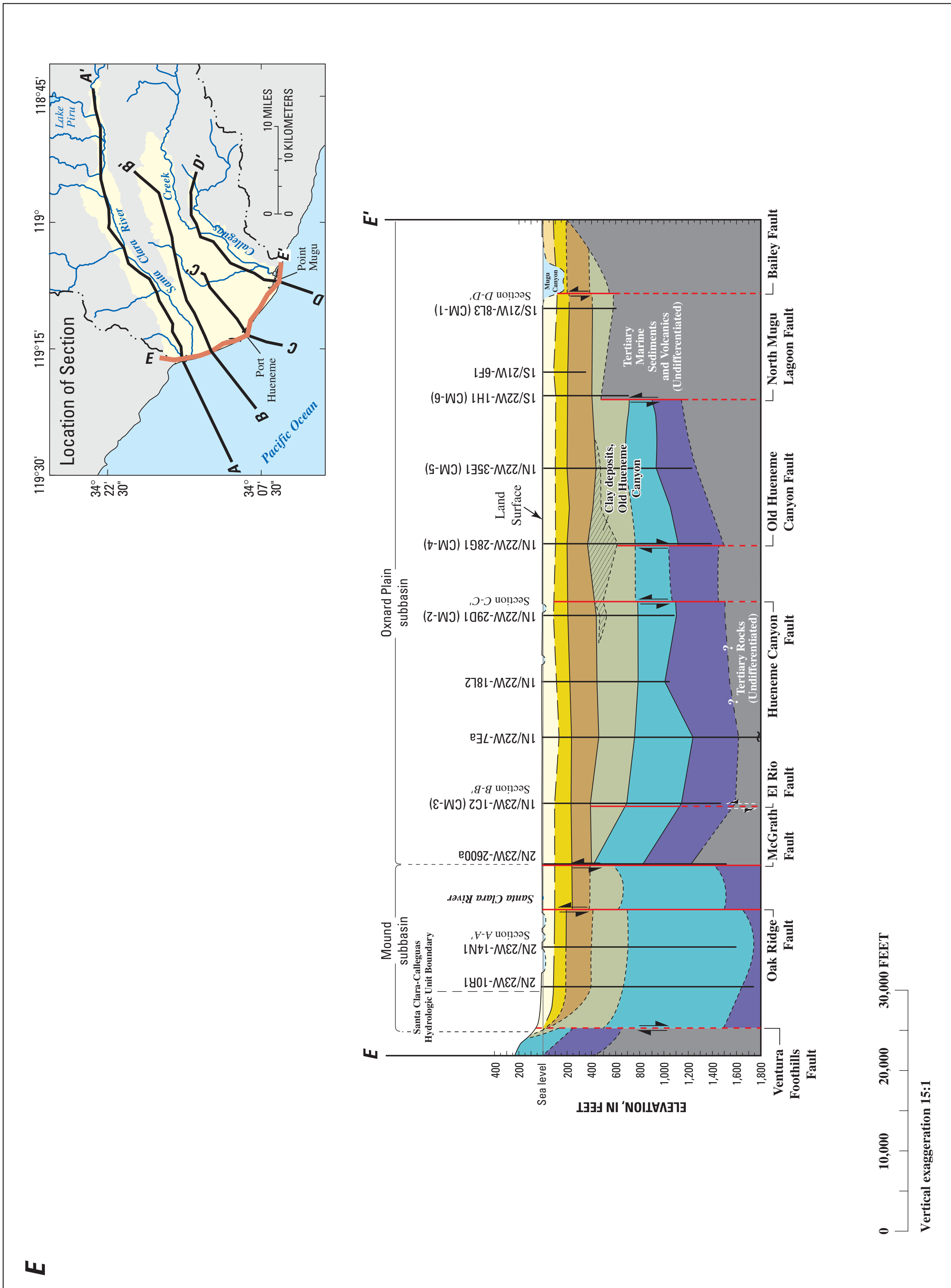


Figure 8—Continued.

Aquifer Systems

The water-bearing deposits were previously divided into six aquifers in the Santa Clara–Calleguas Basin within the two regional aquifer systems (Turner, 1975). Using geophysical and geochemical data collected as a part of the USGS RASA Program, the aquifer designations were realigned into seven major aquifers. The unconsolidated deposits of the late Pleistocene and Holocene epochs are grouped into the regional upper-aquifer system, which includes the Shallow, Oxnard, and Mugu aquifers (fig. 7*B*). The lower-aquifer system is composed of complexly faulted and folded unconsolidated deposits of the Pliocene and Pleistocene epochs and include the upper and lower Hueneme, Fox Canyon, and Grimes Canyon aquifers (fig. 7*B*). The lower aquifer extends to about 1,600 ft below sea level in the Oxnard Plain subbasin to more than 2,000 ft below sea level in the Mound subbasin (fig. 8 *A*,*E*). All these aquifers extend offshore within the continental shelf (fig. 8); however, the thickness, structure, and extent of the submarine outcrops vary across the basin for the upper- and lower-aquifer systems (figs. 7 and 8).

The onshore part of the Oxnard Plain is subdivided into a confined region and an unconfined region. The unconfined region includes the Oxnard Plain Forebay and the northeastern part of the Oxnard Plain. The confined region was subdivided into Northwest and South Oxnard Plain model subareas for the water-management analysis in this study (fig.1). The submarine shelf extends (fig. 7*A*) southwestward from the coastline and is subdivided along the McGrath Fault as an extension of the onshore separation between the Mound subbasin and the Oxnard Plain (figs. 1 and 7); these subbasins are hereinafter referred to as the "offshore Mound" and "offshore Oxnard Plain" subbasins. For the water-management analysis in this study, the offshore Oxnard Plain was subdivided into northern and southern regions separated by the Hueneme submarine canyon.

Upper-Aquifer System

Shallow Aquifer—The Shallow aquifer extends from land surface to a depth of 60 to 80 ft along the Santa Clara and the Arroyo Las Posas flood plains and throughout most of the Oxnard Plain and Pleasant Valley subbasins (figs. 7 and 8). Along the flood plain of the Santa Clara River, the shallow aquifer consists of predominantly sand and gravel and is an important source of ground water. During prolonged droughts, the Shallow aquifer becomes dewatered in the upper reaches of the Santa Clara River and Arroyo Las Posas. Beneath the Oxnard Plain and Pleasant Valley subbasins, the Shallow aquifer consists of fine-to-medium sand with interbedded clay layers and is referred to as the "semiperched aquifer"; the clay layers separate the Shallow aquifer from the underlying Oxnard aquifer. The Shallow aquifer occasionally becomes perched locally because of pumping from the Oxnard aquifer. Water quality is poor throughout most of the Oxnard Plain and Pleasant Valley subbasins and consequently few wells are perforated opposite this aquifer.

Oxnard Aquifer—The Oxnard aquifer lies at the base of the Holocene deposits and consists of sand and gravel deposited by the ancestral Santa Clara River and the Calleguas Creek and by their major tributaries. The coarse-grained basal deposits of the Holocene epoch are referred to as the "Oxnard aquifer" (Turner, 1975). The base of the aquifer ranges from about 150 to 250 ft below land surface throughout most of the Oxnard Plain subbasin (fig. 8). The basal deposits range in thickness from less than 10 to 200 ft and are a major source of water to wells in the Piru, Fillmore, Santa Paula, Oxnard Plain Forebay, and Oxnard Plain subbasins. Hydraulic conductivity in the Oxnard aquifer is about 190 ft/d near Port Hueneme (Neuman and Witherspoon, 1972). The Oxnard aquifer is relatively fine grained in the Mound, Pleasant Valley, Santa Rosa Valley, and Las Posas Valley subbasins; this aquifer is not considered an important source of ground water in these subbasins. Throughout most of East and West Las Posas Valley subbasins, the Oxnard aquifer is unsaturated.

In the Piru and Fillmore subbasins, there are few if any clay layers separating the Shallow and Oxnard aquifers; therefore, ground water can move freely between the two. In the Santa Paula subbasin, the Santa Clara River has migrated south of the ancestral river that deposited the sediments of the Oxnard aquifer and mostly overlies non-water-bearing rocks of Tertiary age. As a result, the Santa Clara River does not overlie the Oxnard aquifer throughout most of the Santa Paula subbasin.

In the Oxnard Plain Forebay subbasin, there are relatively few clay layers separating the Shallow and Oxnard aquifers. Alluvial fans derived from the mountains north of the Mound subbasin pushed the Santa Clara River south toward South Mountain. In the Oxnard Plain Forebay subbasin, clay layers were eroded by the Santa Clara River, and sand and gravel were deposited in their place; owing to the absence of clay, this subbasin is artificially recharged by surface spreading of water diverted from the Santa Clara River. The Oxnard aquifer is considered to be unconfined in the Oxnard Plain Forebay subbasin.

Throughout the Oxnard Plain and Pleasant Valley subbasins, the Shallow and Oxnard aquifers are separated by clay layers. These clay layers confine or partly confine the Oxnard aquifer throughout most of the Oxnard Plain and Pleasant Valley subbasins. Previous investigators (California Department of Water Resources, 1956; Turner, 1975) reported that the clay layers separating the Shallow and Oxnard aquifers in the Point Mugu area are thin or absent, allowing free interchange of water in this part of the subbasin. However, data, collected from several multiple-well monitoring sites constructed in the Point Mugu area as a part of this study (Densmore, 1996), indicate that relatively thick clay layers separate the Shallow and Oxnard aquifers.

Mugu aquifer—The Mugu aquifer (Turner, 1975) is composed of the basal part of the unnamed upper Pleistocene deposits. In the Piru, Fillmore, Santa Paula, Mound, Oxnard Plain Forebay, and Oxnard Plain subbasins, these deposits are similar to those of the underlying lower-aquifer system because the Santa Clara River was the primary source of sediment for both aquifers. The Mugu aquifer is differentiated from the lower-aquifer system because it is less indurated and relatively undisturbed. However, because of the similarities between these deposits, many investigators include the upper Pleistocene deposits in the lower-aquifer system. In the Pleasant Valley, Santa Rosa Valley, East Las Posas Valley, and West Las Posas Valley subbasins, the Mugu aquifer sediments were derived from South Mountain and the surrounding hills and are finer grained than sediments derived from the Santa Clara River.

Throughout most of the ground-water basin, the Mugu aquifer extends from about 200 to 400 ft below land surface (fig. 8) and consists of sand and gravel interbedded with silt and clay. The silt and clay layers retard the vertical movement of water through the Mugu aquifer and confine or partly confine the aquifer. Over most of the ground-water basin, the top of the aquifer is relatively flat; however, the base of the aquifer has a more irregular surface (Turner, 1975) owing to a regional uncomformity. This uncomformity, which is most pronounced in the Mound and the East Las Posas Valley subbasins (fig. 8*A*,*B*,*E*), is due to deformation during deposition of older alluvium that contains the Mugu aquifer.

Few production wells are perforated solely in the Mugu aquifer; most are also perforated in the overlying Oxnard aquifer or in the underlying lower-aquifer system. In general, wells that are perforated opposite both the Oxnard and Mugu aquifers, which are similar in thickness, obtain most of their water from the Oxnard aquifer because it is significantly more permeable. Hydraulic conductivities estimated from slug tests at the multiple-well monitoring sites constructed for this study range from less than 1 to 98 ft/d; most, however, are less than 25 ft/d (E.G. Reichard, U.S. Geological Survey, written commun., 1995). When individual wells at the same multiple-well monitoring site were tested, the estimated hydraulic conductivity of the Oxnard aquifer was almost always higher than that estimated for the Mugu aquifer.

In subbasins in which the Mugu aquifer is predominantly coarse-grained (the Piru, Fillmore, and Santa Paula subbasins), wells perforated in both the Mugu aquifer and the underlying lower-aquifer system obtain most of their water from the Mugu aquifer. This is shown by a wellbore flowmeter test completed on well 3N/21W–11J5 in the Santa Paula subbasin (see figure A5.1 in Appendix 5). Although this well is perforated predominantly in the lower-aquifer system, almost all the water yielded by the well is derived from the Mugu aquifer. As stated previously, the Mugu aquifer is less indurated than the lower-aquifer system, which would account for its greater water-yielding capacity. In the subbasins where the Mugu aquifer is predominantly fine grained, wells yield significant quantities of water from the aquifer only if they are perforated opposite the basal coarse-grained zone. This laterally extensive basal zone, which, as noted earlier, is due to a regional unconformity, yields water readily to wells. Many wells are not perforated opposite this zone, however, because its thickness is 20 ft or less throughout many of the subbasins. Results of the wellbore flowmeter test for well 1N/21W–15D2 (figure A5.1 in Appendix 5) in the Pleasant Valley subbasin show that the basal zone of the Mugu aquifer yields significantly more water per foot of aquifer penetrated than does the underlying lower-aquifer system.

Lower-Aquifer System

The lower-aquifer system consists of the folded and faulted Pleistocene continental and marine deposits of the Saugus, San Pedro, and Santa Barbara Formations as defined by Weber and others (1976) and the Saugus Formation and the Las Posas Sand as defined by Dibblee (1988, 1990a,b, 1991, 1992a,b,c,d) and by Dibblee and Ehrenspeck (1990). For this study, the unconsolidated deposits of the Saugus and the upper part of the San Pedro Formations as defined by Weber and others (1976) and the Saugus as defined by Dibblee were split into the “Upper Hueneme” and “Lower Hueneme” aquifers, respectively, for the entire Santa Clara–Calleguas Basin (fig. 7*B*). The lower part of the San Pedro Formation as defined by Weber and others (1976) and the upper part of the Las Posas Sand as defined by Dibblee are referred to as the “Fox Canyon aquifer” in the Las Posas, Pleasant Valley, and Oxnard Plain subbasins (Turner, 1975). The coarse-grained layers of the Santa Barbara Formation as defined by Weber and others (1976) are commonly referred to as the “Grimes Canyon aquifer” in the East Las Posas Valley subbasin and parts of the Pleasant Valley subbasins (Turner, 1975). In most of the other subbasins, the Santa Barbara Formation is of low permeability, yields poor-quality water, and is not considered an important source of water. Regional fault systems (figs. 7 and 8) segregate the lower-aquifer system into many parts and affect the flow of water between and within the subbasins.

Upper and Lower Hueneme Aquifers—The Hueneme aquifers constitute the upper part of the San Pedro Formation beneath the Oxnard Plain mapped by Weber and others (1976), and the Saugus Formation beneath the Santa Clara River Valley subbasins mapped by Dibblee (1988, 1990a,b, 1991, 1992a,b,c,d) and Dibblee and Ehrenspeck (1990). These aquifers consist of lenticular layers of sand, gravel, silt, and clay. The sediments constituting the aquifers have been subjected to considerable folding, faulting, and erosion since deposition. These deposits were divided into upper and lower aquifers based on data from electric logs which show a decrease in electrical resistivity at the contact between the aquifers. The decrease is attributed to the presence of more fine-grained deposits in the Lower Hueneme aquifer than in the Upper Hueneme. The Upper Hueneme aquifer reaches a maximum thickness of more than 700 ft (fig. 8*A*) and the Lower Hueneme aquifer reaches a thickness of more than 2,000 ft in the axis of the Santa Clara syncline in the Santa Paula, Fillmore, and Piru subbasins. In areas of the basin that have been uplifted since deposition (fig. 8*A*,*D*,*E*), much of the sediments constituting Hueneme aquifers have been removed by erosion.

In the Oxnard Plain subbasin, the Upper Hueneme aquifer is predominantly fine grained in two areas along the coast line between Port Hueneme and Point Mugu (Old Hueneme Canyon on figure 8*C*,*E*). These fine-grained deposits are more than 200 ft thick near the coast, and they extend about 3.5 mi inland. Turner (1975) attributed these deposits to a lagoonal or embayment depositional environment throughout most of the San Pedro Formation deposition. Inspection of lithologic and electrical logs collected during the drilling of the multiple-well monitoring sites constructed for this study indicates that these fine-grained deposits are ancestral submarine canyons (fig. 8*C*,*E*) that were backfilled during a rise in sea level. The submarine canyons were carved into the San Pedro Formation sometime prior to the deposition of the deposits of the upper Pleistocene. These backfilled ancestral submarine canyons are important hydrologic features because they are low permeable barriers to ground-water flow and may contribute to coastal subsidence (fig. 9). The hydraulic conductivity of the fine-grained deposits in the ancestral submarine canyon, estimated from a slug test at the CM-5 multiple-well monitoring site (fig. 8*E*), was 0.1 ft/d (E.G. Reichard, U.S. Geological Survey, written commun, 1995).

Fox Canyon Aquifer—The Fox Canyon aquifer constitutes the basal part of the San Pedro Formation mapped by Weber and others (1976). The aquifer consists of weakly indurated very fine- to medium-grained fossiliferous sand with occasional gravel and clay layers of shallow marine origin. As stated previously, Dibblee (1992a,b,c,d) mapped these deposits as a separate formation, which he designated as the Las Posas Sand. The marine deposition of the sediments of the Fox Canyon aquifer resulted in a relatively uniform series of layers, which can be correlated by the electric logs, over large areas of the ground-water basin (Turner, 1975). The Fox Canyon aquifer is identified on electric logs by zones of relatively high resistivity that are almost identical for thicknesses of 100 to more than 300 ft. In contrast, the overlying Lower Hueneme aquifer is characterized as a series of relatively high resistivity zones 10 to 100 ft in thickness separated by relatively low resistivity zones 10 to 20 ft in thickness. Most of the electric logs inspected show there was a significant shift in the spontaneous potential curve opposite the Fox Canyon aquifer, indicating a change in the aquifer mineralogy and (or) a change in the water quality of the aquifer.

Historically, very few wells tapped the Fox Canyon aquifer of the ground-water basin, except in the East and West Las Posas Valley and the Pleasant Valley subbasins. Because yield is significantly less in this aquifer than in the upper aquifer system, few water wells were perforated solely in the Fox Canyon aquifer. This limited testing of the hydraulic properties of the aquifer. For previous investigations, electric logs from petroleum wells were used to define the character and extent of the aquifer. High-resistivity zones on those logs, which indicate possible coarse-grained zones of good quality water, led to the belief that the Fox Canyon aquifer would be a major source of water to wells.

To help determine the hydraulic properties of the Fox Canyon aquifer, at least one piezometer at 13 of the 23 multiple-well monitoring sites constructed for this study was perforated opposite the aquifer. The lithologic and electric logs for these sites indicate relatively low permeability; the Fox Canyon aquifer consists of predominantly fine- to very fine-grained sand that is indurated to slightly indurated (Densmore, 1996); this is coincident with the high-resistivity zones on the electric logs and reflects the low dissolved-solids concentration of water in the aquifer and the induration of the aquifer sediments. The low permeabilities were confirmed by slug tests that indicate hydraulic conductivities ranging from 1 to 9 ft/d (E.G. Reichard, U.S. Geological Survey, written commun., 1995). These hydraulic conductivities are considerably lower than those of the overlying aquifers.

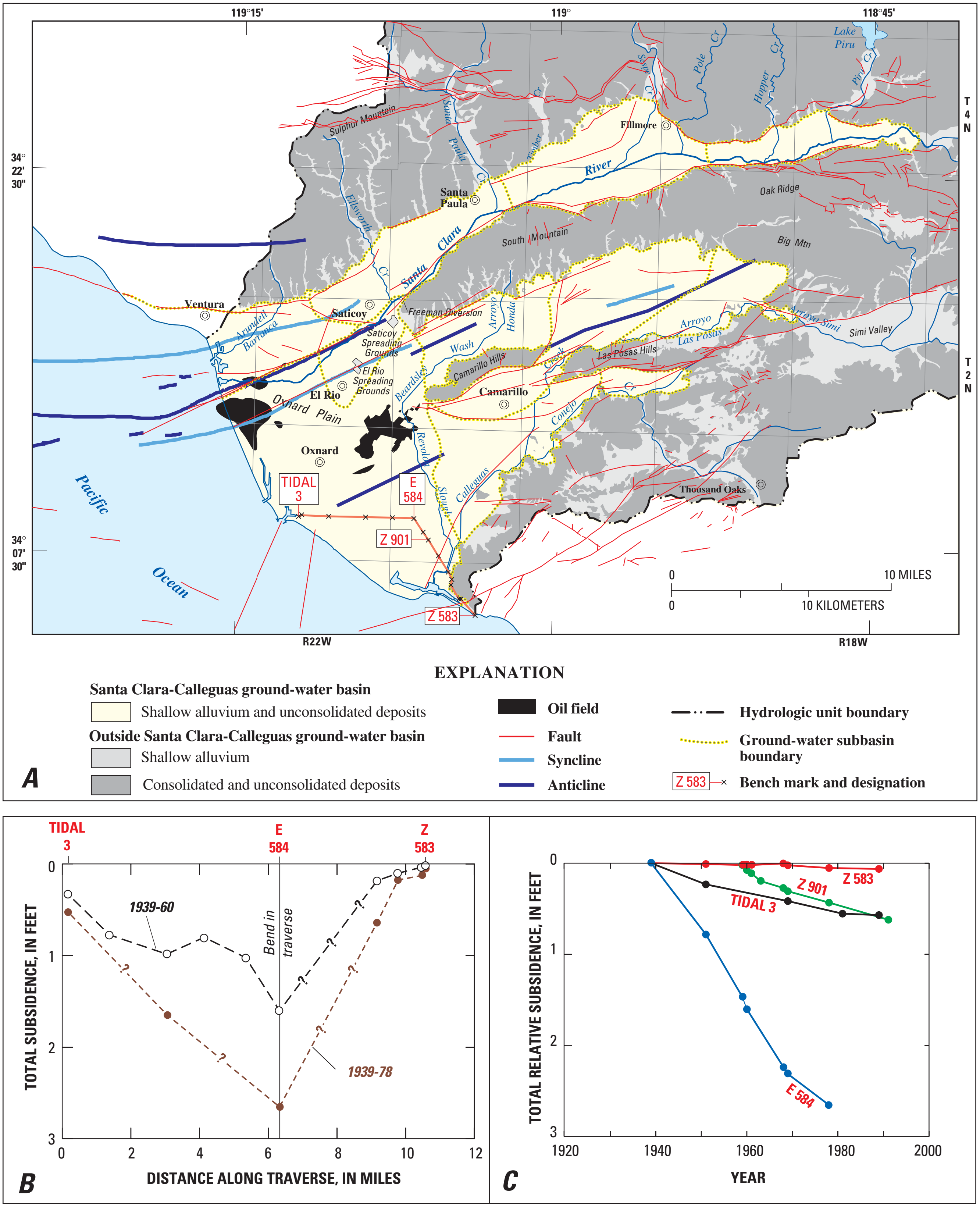


Figure 9. Subsidence in Oxnard Plain and Pleasant Valley, Santa Clara–Calleguas ground-water basin, Ventura County, California. ***A***, Geographic features. ***B***, Subsidence profile. ***C***, Subsidence of bench marks through time.

To determine the relative contribution of water from the Fox Canyon aquifer to wells perforated in the Fox Canyon and overlying aquifers, available flowmeter logs were inspected and additional logs were collected (see table 5 in the "Ground-Water Discharge" section). The flowmeter log collected at well 2N/22W-13N2 in the Oxnard Plain Forebay subbasin (in Appendix 5) shows that little, if any, water enters the wells from the Fox Canyon aquifer, and almost all the water pumped comes from the basal zone of the overlying Lower Hueneme aquifer. Flowmeter logs collected from wells in the Oxnard Plain and the Pleasant Valley subbasins indicate that, in most of the wells tested, the flow contribution from the Fox Canyon aquifer is less than the flow contribution from the overlying aquifers. Data from the flowmeter logs from the Pleasant Valley and the Oxnard Plain subbasins indicate that the Fox Canyon aquifer is a major source of water to wells perforated throughout the lower-aquifer system only if the overlying Lower Hueneme aquifer is absent or is predominantly fine grained. Based on well construction data, this may be the case throughout most of the East and West Las Posas Valley, Oxnard Plain, and Pleasant Valley subbasins.

Grimes Canyon Aquifer—The Santa Barbara Formation (Weber and others, 1976), which consists of non-water-bearing marine sandstone, siltstone, mudstone, and shale, underlies the Fox Canyon aquifer throughout most of the ground-water basin and is considered the base of the ground-water system throughout most of the basin. However, in parts of the ground-water basin, the upper part of the Santa Barbara Formation contains water-bearing deposits referred to as the "Grimes Canyon aquifer" (Turner, 1975).

In the East Las Posas Valley subbasin, the Grimes Canyon aquifer predominantly consists of layers of well-indurated sandstones and conglomerate with high resistivity as indicated by the electric logs, characteristic of well-indurated sandstone and conglomerate layers. Because the sediments are well indurated, the hydraulic conductivity of the aquifer is relatively low. However, the Grimes Canyon aquifer is an important source of water in the East Las Posas Valley subbasin where the overlying aquifers are absent or are unsaturated.

The Grimes Canyon aquifer is also present in the southeastern part of the Oxnard Plain subbasin and throughout most of the Pleasant Valley subbasins (Turner, 1975); many production wells tap this aquifer throughout the Pleasant Valley subbasin. Lithologic and electric logs collected from multiple-well monitoring sites constructed for the RASA study indicate that much of the deposits that contain the Grimes Canyon aquifer are relatively fine grained and water is relatively high in dissolved-solids (Densmore, 1996). Although deposits similar to those of the Grimes Canyon aquifer are present beneath the western part of the Oxnard Plain subbasin, few production wells tap these deposits owing to their greater depth in that part of the subbasin.

Ground-Water Recharge

Sources of recharge to the aquifer systems include streamflow infiltration, direct infiltration of precipitation on the valley floors of the subbasins and on bedrock outcrops in adjacent mountain fronts, artificial recharge of diverted streamflow and imported surface water, percolation of treated sewage effluent, and infiltration of excess irrigation water (irrigation return flow) in some agricultural areas. For previous studies, recharge was estimated using consumption and water-balance methods based on precipitation and streamflow data for various historical periods (Grunsky, 1925; California Department of Public Works, 1934; California State Water Resources Board, 1956; Mann and Associates, 1959; California Department of Water Resources, 1975).

Streamflow Infiltration

Streamflow infiltration is the largest component of ground-water recharge in the Santa Clara–Calleguas basin and includes gaged and ungaged streamflow. The Santa Clara River and the Calleguas Creek have been altered substantially by regulated flow; the construction of the Santa Felicia Dam (Lake Piru) transformed flow in the Santa Clara River system from predominantly winter and spring floodflows to significant summer and fall low flows.

Gaged Streamflow

Previous estimates of annual subbasin streamflow-infiltration rates are summarized in table 3. These reported estimates were aggregated into averages for the wet and dry periods used in this study (fig. 2*A*). The total estimated gaged streamflow infiltration reported by the California Department of Water Resources (1975) for 1937–67 ranged from 0 to 297,700 acre-ft annually (table 3). These estimates yield average wet-year and dry-year infiltration rates that are 67 and 57 percent of estimated runoff, respectively. The ratios of wet-year to dry-year infiltration for the Santa Clara River and for the total basin during the period were 2.0 and 2.7, respectively (table 3). For streamflows less than 250 ft^3/s (about 500 acre-ft/d), the rates of infiltration on the Santa Clara River were about 14 percent, and for several dry years (such as 1952 and 1958) the rates ranged from 50 to 70 percent (California Department of Water Resources, 1975, fig. 15).

Streamflow loss for the Santa Clara River for wet and dry seasonal flows less than 250 ft^3/s (about 500 acre-ft/d) was determined by subtracting downstream gaged streamflow (gaging station 11114000) from the sum of upstream gaged inflows (gaging stations 11108500, 11110000, 11110500, 713, 11113000, 11113500) (fig. 4). Similarly, the streamflow loss for Calleguas Creek was estimated as the difference between downstream streamflow (11106550) and gaged inflows (11106850 and 11106400) for flows less than 10 ft^3/s (20 acre-ft/d) (fig. 4). Seasonal streamflow losses in the Santa Clara River and the Calleguas Creek varied widely but generally show several patterns (fig. 10). Regression of seasonal streamflow loss in relation to total gaged streamflow indicates an overall loss of 35 percent for wet-year seasons (fig. 10*A*) and 52 percent for dry-year seasons (fig. 10*B*) for the Santa Clara River. Loss from the Calleguas Creek during low-flow conditions is generally either 0 percent during winter and fall seasons or 100 percent during spring and fall seasons (fig. 10*C*). During dry-year summers, 70 to 100 percent of the flow in the Santa Clara River is lost to ground-water recharge (fig. 10*B*). Streamflow loss is low for many of the wettest years, such as 1969 and 1984 (fig. 10*A*), which may indicate a significant contribution of ungaged inflow prior to or during periods with relatively low flow (less than 200 ft^3/s). The annual range of gaged streamflow loss in the Santa Clara River for 1956–93 varied from about 2,700 to 97,800 acre-ft/yr (table 3). On a climatic basis, total infiltration for the Santa Clara River was about 34,000 (22 percent of flow) and 25,100 (37 percent of flow) acre-ft/yr for wet- and dry-year periods during 1956–93, respectively; for the Calleguas Creek above Highway 101, it ranged from 0 to 6,100 acre-ft/yr for the period of record (1973–93) (table 3). The wide range of streamflow loss also was subject to the effects of additional inflow from treated municipal sewage between gaging stations of about 12 ft^3/s (8,700 acre-ft/yr) and irrigation return flow.

Streamflow infiltration along the Santa Clara River, estimated as part of a sediment-transport study, is 23 percent of flow per mile for flows less than 100 ft^3/s, 20 percent of flow per mile for flows from 100 to 500 ft^3/s, 6 percent of flow per mile for flows from 500 to 1,000 ft^3/s, and less than 2 percent of flow per mile for floodflows greater than 1,000 ft^3/s (Brownlie and Taylor, 1981).

Densmore and others (1992) estimated streamflow infiltration for a summer drought under conditions of controlled releases from Lake Piru. The controlled releases result in an increase in infiltration rate with increased channel width in Piru Creek when releases exceed 200 ft^3/s (Steve Bachman, United Water Conservation District, oral commun., 1996).

These various infiltration estimates collectively suggest that infiltration is dependent on antecedent conditions, which include antecedent ground-water levels; magnitude of the streamflow and related properties, such as channel width; and current and antecedent regulated flows.

Table 3. Summary of estimated ranges and averages of gaged and ungaged streamflow infiltration in the Santa Clara-Calleguas Basin, Ventura County, California

[Time periods are reported in water years except from this study. All estimates are in acre-feet per year. Numbers in parentheses are average infiltration values during dry and wet periods, respectively. —, no estimate was made]

Time period of estimate	Streamflow infiltration					Total infiltration		Basin total infiltration
	Gaged				Ungaged			
	Piru	Fillmore	Santa Paula	Montalvo Forebay of Oxnard Plain	Mountain-Front Recharge	Santa Clara River	Calleguas Creek	
1893 to [1]1932	—	—	—	—	1,400–56,200 [2] (11,500; 30,200)	12,300–138,900 (51,300; 65,000)	—	12,400–143,300 [1](62,500; 99,800)
1937 to [3]1951	6,800–68,600 (18,500; 38,400)	0–33,600 (0; 0)	0–16,200 (4,100; 9,300)	1,000–145,000 (23,600; 74,600)	—	—	—	—
1937 to [4]1957	6,400–68,300 (19,100; 36,100)	1,800–49,100 (20,500; 26,800)	4,200–24,400 (14,900; 15,700)	1,000–39,300 (12,100; 22,100)	—	—	—	—
1937 to [5]1967	—	—	—	—	3,600–190,000 (22,400; 80,300)	0–185,800 (26,400; 51,800)	—	0–297,700 (40,300; 108,600)
1956 to [6]1993	—	—	—	—	3,800–78,500 (13,200; 34,200)	2,700–97,800 (25,100; 34,000)	0–6,100	—

[1]Estimates from the California Department of Public Works (1934, table 59). For Santa Clara River, the net streamflow includes estimates of runoff from ungaged tributaries and valley-floor runoff.
[2]Estimates include only the Santa Clara River Valley.
[3]Estimates from the California State Water Resources Board (1956, tables 12–15).
[4]Estimates from Mann (1959), Plates 28–31
[5]Estimates from the California Department of Water Resources (1975, tables 23 and 24). For basin total the net streamflow includes estimates of runoff from ungaged tributaries.
[6]Estimates from this study. Streamflow leakage for Calleguas Creek does not include additional streamflow infiltration from treated waste water or irrigation returnflow.

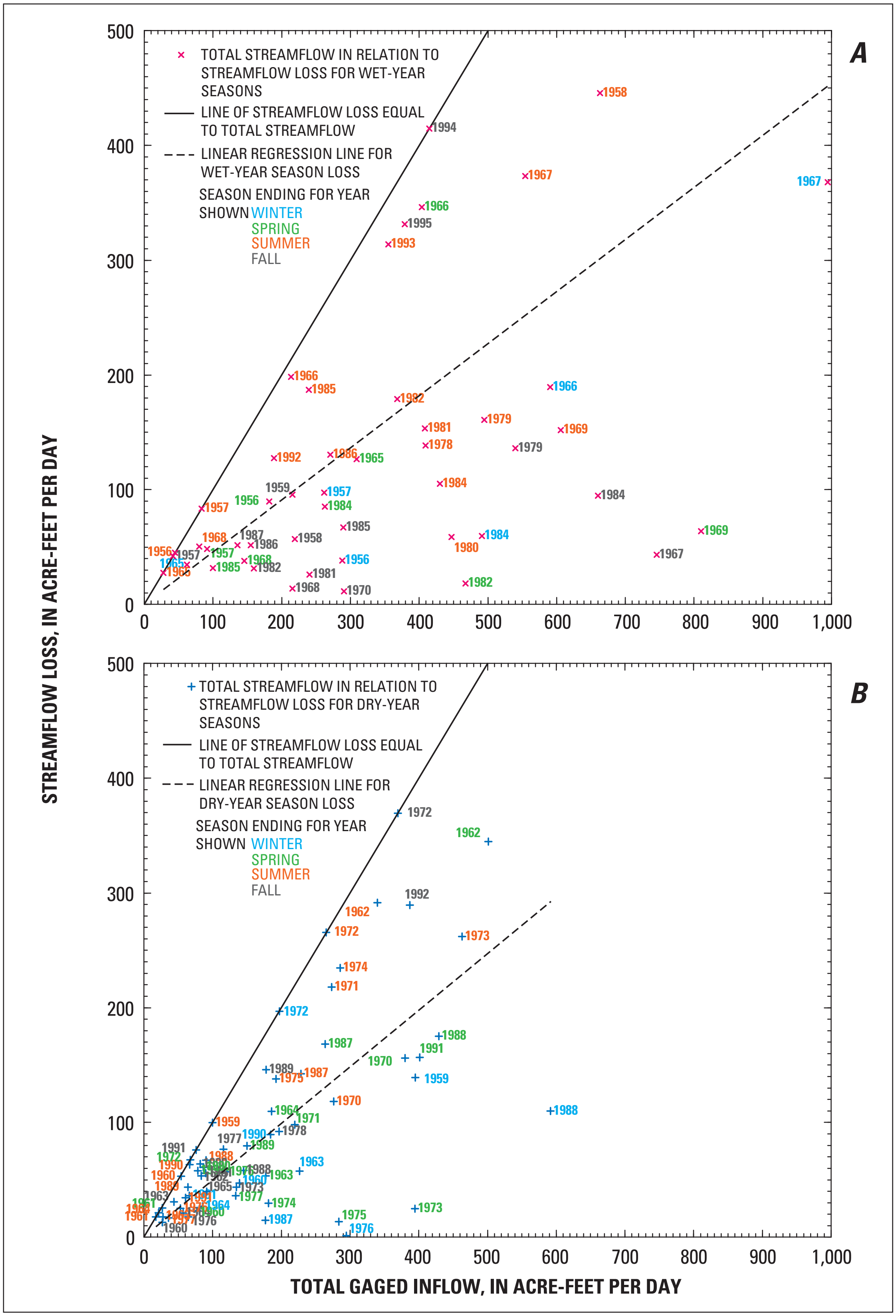


Figure 10. Estimated seasonal streamflow losses for gaged inflows in the Santa Clara River and Calleguas Creek and tributaries, Ventura County, California. ***A***, Santa Clara River streamflow in wet-years seasons. ***B***, Santa Clara River streamflow in dry-year seasons. ***C***, Calleguas Creek streamflow in wet-and dry-year seasons.

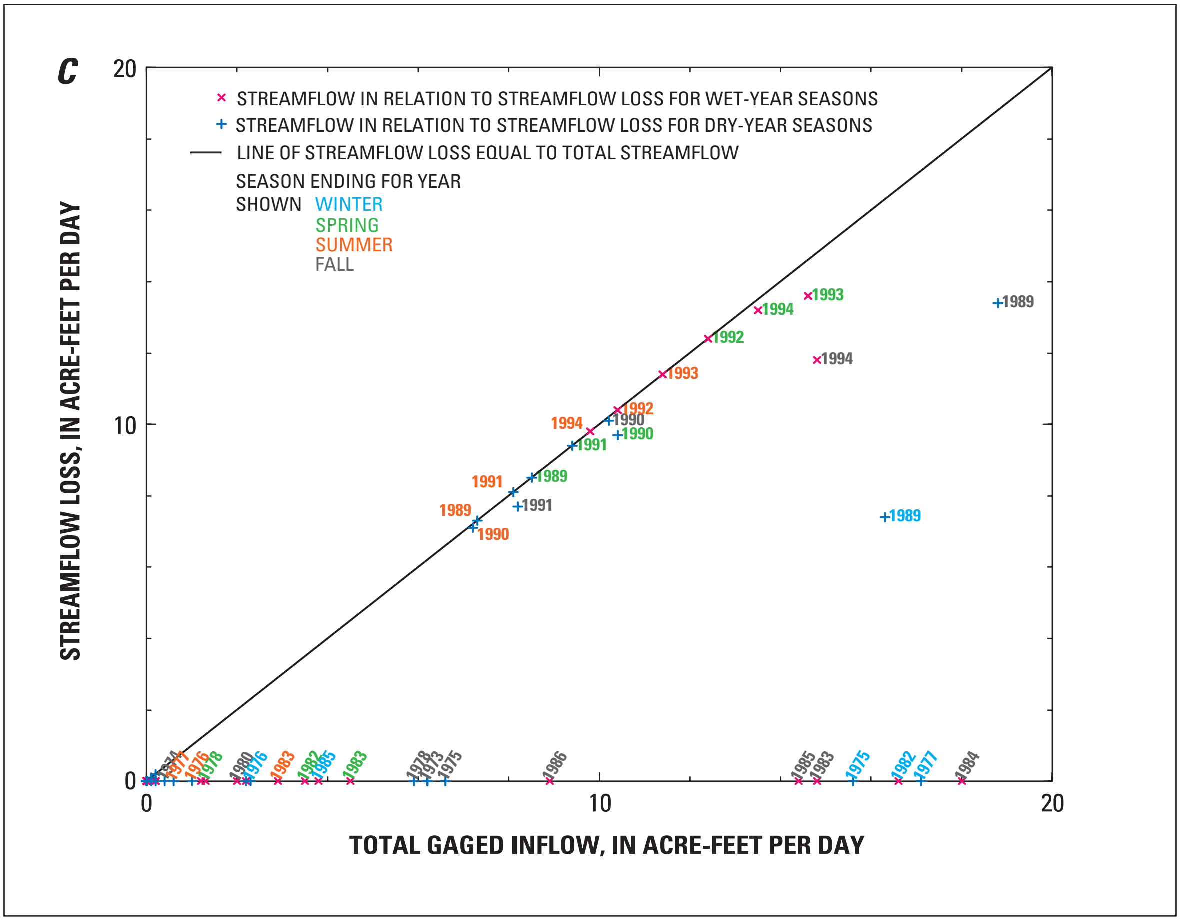


Figure 10—Continued.

Ungaged Streamflow

Infiltration of streamflow in ungaged drainage basins at the boundary of an alluvial aquifer system is referred to as “mountain-front recharge.” Mountain-front recharge occurs along the arroyos and the small tributary stream channels of the 64 ungaged tributary drainage basins that drain into the ground-water subbasins from the surrounding mountain fronts of the Santa Clara–Calleguas Basin. This component of streamflow constitutes a small but significant contribution to streamflow and ground-water recharge, especially during wet years. For this study, it was assumed that the streamflow percolates into the alluvium and becomes ground-water recharge. This assumption may result in an overestimate of recharge during floodflows.

Previous estimates of mountain-front recharge range from 1,400 to 190,000 acre-ft/yr for 1893–1967 (table 3). In some wet years such as 1969, 1978, 1979, 1980, 1983, 1986, and 1993, measured outflow at the downstream gaging station at Montalvo (11114000) (fig. 4) on the Santa Clara River was greater than gaged inflow from the major tributaries. This difference can be attributed to the contribution of ungaged streamflow. Based on gaging-station data, this ungaged streamflow may have ranged from 39,800 to 479,800 acre-ft/yr for the Santa Clara River for 1956–93 and from 300 to 7,800 acre-ft/yr for Calleguas Creek for 1973–93 (the period of record).

For this study, mountain-front recharge was estimated by means of a modified rational method using gaged streamflow data from two small subdrainage basins, Hopper and Pole Creeks (fig. 4), referred to as "index" basins. The fraction of precipitation assumed to be mountain-front recharge was estimated as the ratio of total seasonal streamflow for each ungaged subdrainage basin to the average total seasonal precipitation for an index basin. To estimate mountain-front recharge, estimates of seasonal precipitation were required for each of the subdrainage basins for each wet year and dry year (fig. 3). It was assumed that most of the runoff from the ungaged drainage basins infiltrates near the mountain fronts and does not contribute significantly to mainstem streamflow.

The amount of recharge was estimated as the index-basin streamflow fraction of precipitation multiplied by the average total volume of seasonal precipitation (drainage area multiplied by kriged seasonal precipitation) for each of the 64 ungaged tributary subdrainage basins. Seasonal (winter, spring, summer, and fall) estimates for wet and dry years were made for all 64 subdrainage subbasins. The average percentages of precipitation that became mountain-front recharge during the period of record for the two index subdrainage basins, Pole and Hopper Creeks, were 4 and 7.5 percent, respectively. Estimates of mountain-front recharge ranged from about 3,800 to 78,500 acre-ft/yr for 1956–93 (table 3) and averaged 34,200 and 13,200 acre-ft/yr for wet- and dry-year periods, respectively. The estimates of seasonal mountain-front recharge ranged from zero for most of the Oxnard Plain to as much as 12,000 acre-ft per season for the Santa Clara River Valley subbasins (figs. 1 and *11A*).

Direct Infiltration

Recharge also occurs as direct infiltration of precipitation on the valley floors (hereinafter referred to as "valley-floor recharge") and as direct infiltration of precipitation on bedrock outcrops (hereinafter referred to as "bedrock recharge"). These components of recharge constitute a small but significant contribution to streamflow and ground-water recharge, especially during wet years.

Previous estimates of direct infiltration for water years 1894 through 1957 (California Department of Public Works, 1934; Mann and Associates, 1959; California Department of Water Resources, 1975) are summarized in table 4. The total estimated infiltration for the Santa Clara River Valley subbasins ranges from 0 to 90,800 acre-ft/yr (table 4) and averages 30,400 and 5,300 acre-ft/yr for wet-year and dry-year periods, respectively (Mann and Associates, 1959).

Direct infiltration was estimated as a percentage of precipitation and ranged from no infiltration in the confined parts of the Mound, Oxnard Plain, and North Pleasant Valley subbasins to as much as 6,238 acre-ft/yr in the unconfined Fillmore subbasin. The percentage of precipitation was based on the modified rational method in which the amount of potential recharge is the fraction of runoff from the index subdrainage basin multiplied by the total volume of precipitation for each ground-water subbasin. This method may overestimate potential recharge during periods of sustained rainfall when soil moisture is exceeded and overland runoff to stream channels occurs. Total estimated recharge as direct (valley-floor) infiltration ranges from 18,300 to 32,700 acre-ft/yr (fig. 11*A*, table 4) during dry- and wet-year periods, respectively; this estimate included an additional 2,200 acre-ft/yr of direct bedrock infiltration along the basin margins, which is described in a later section in the context of developing estimates of inflow for the subareas of the ground-water model.

Artificial Recharge

Artificial recharge is a major contributor to ground-water recharge in the Oxnard Plain Forebay and the Piru subbasins (fig. 11*A*). Artificial recharge was started in 1929 adjacent to Piru and Santa Paula Creeks and the Santa Clara River near Saticoy. The use of streamflows for recharge, as well as for agriculture, supplemented the growing use of the ground-water resources. Additional surface-water storage was provided by construction of Santa Felicia Dam on Piru Creek in the early 1950s. Major diversions along the Piru and Santa Paula Creeks and along the Santa Clara River at Saticoy and Freeman have been used for artificial recharge of the upper-aquifer system.

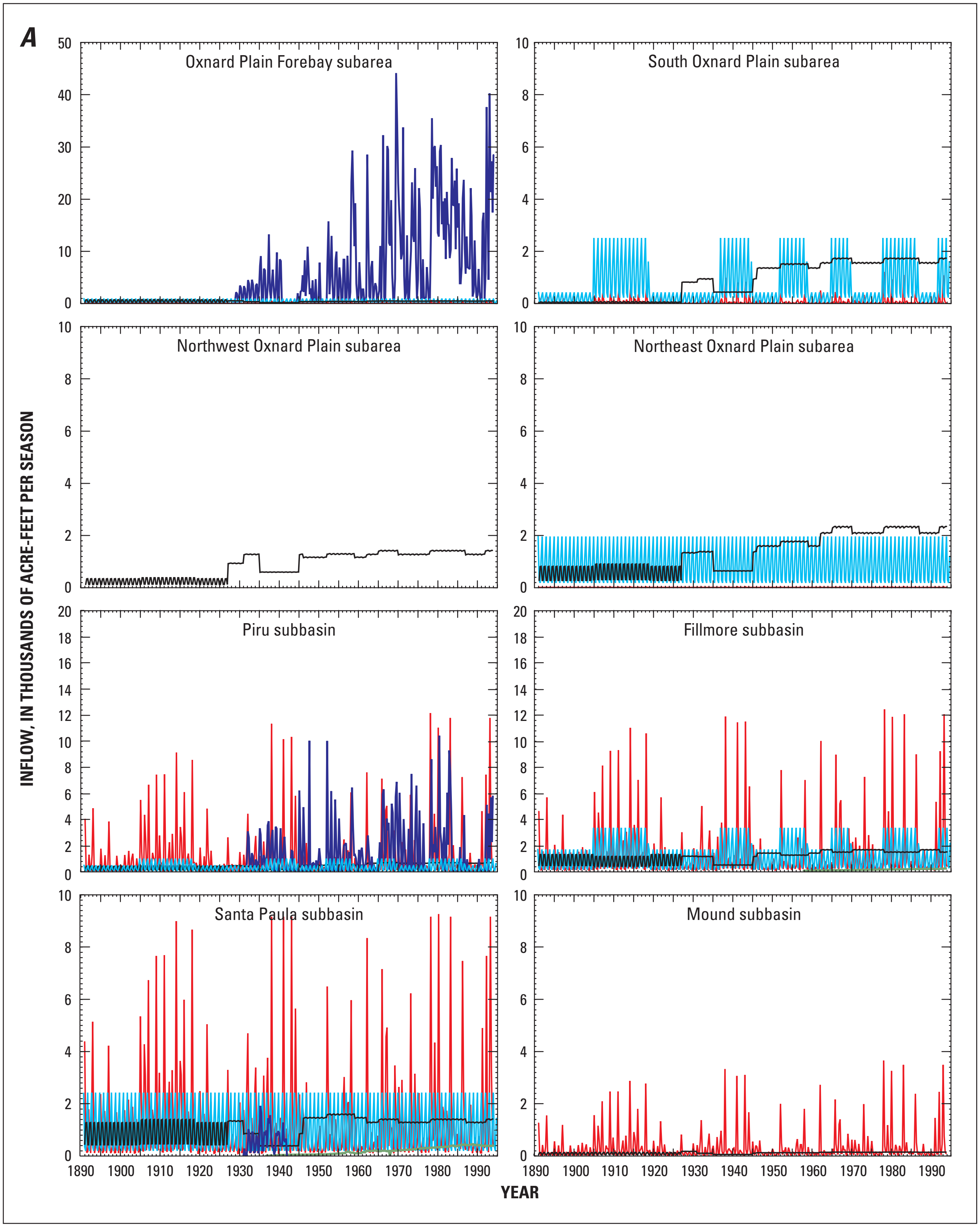
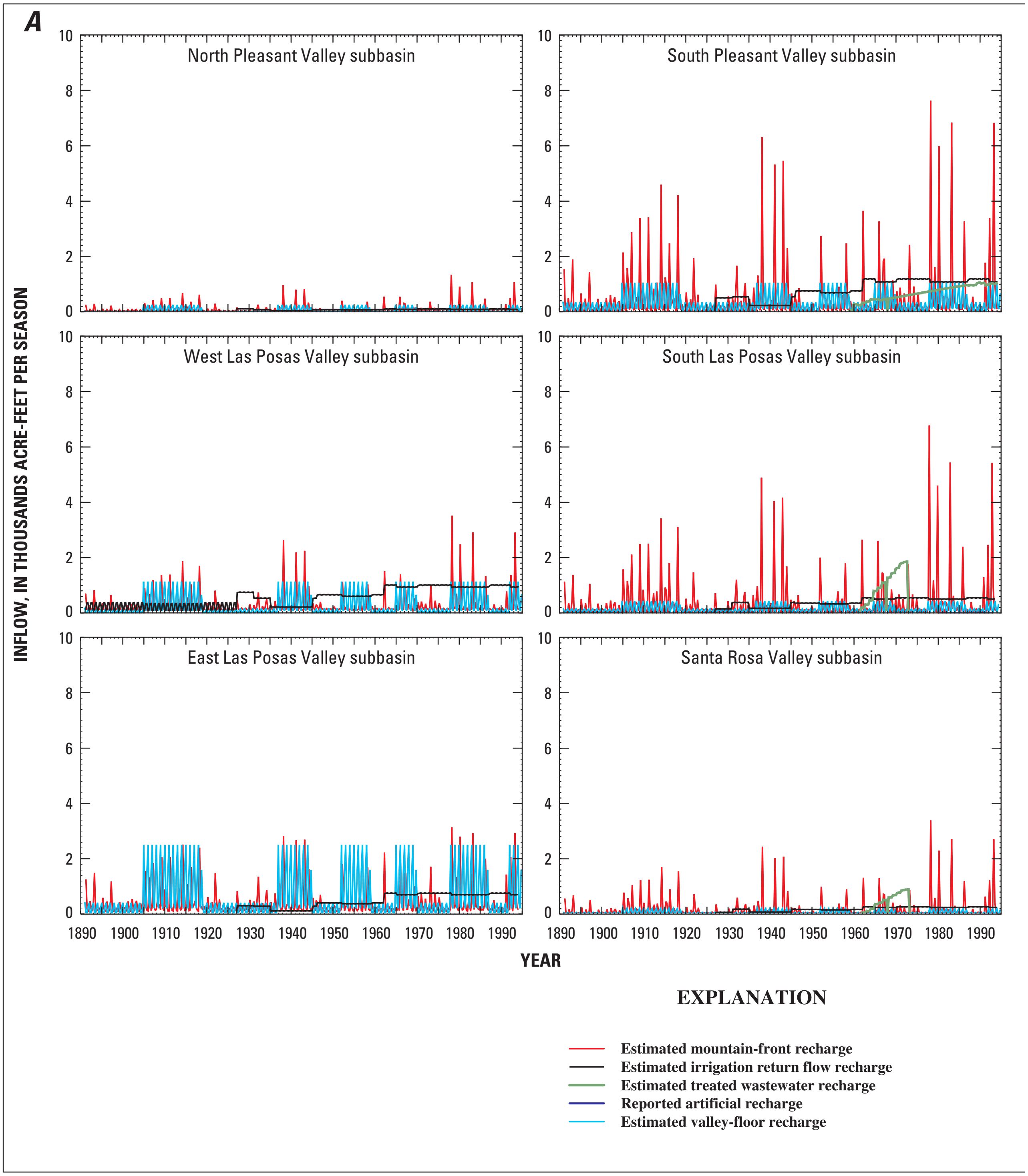


Figure 11. ***A***, Estimates of seasonal ground-water inflows to the subbasins and to the Oxnard Plain subareas of the Santa Clara–Calleguas ground-water basin, Ventura County, California, 1891–1993, and ***B***, Annual estimated and reported ground-water pumpage in the Santa Clara–Calleguas ground-water basin, Ventura County, California, 1891–1993.



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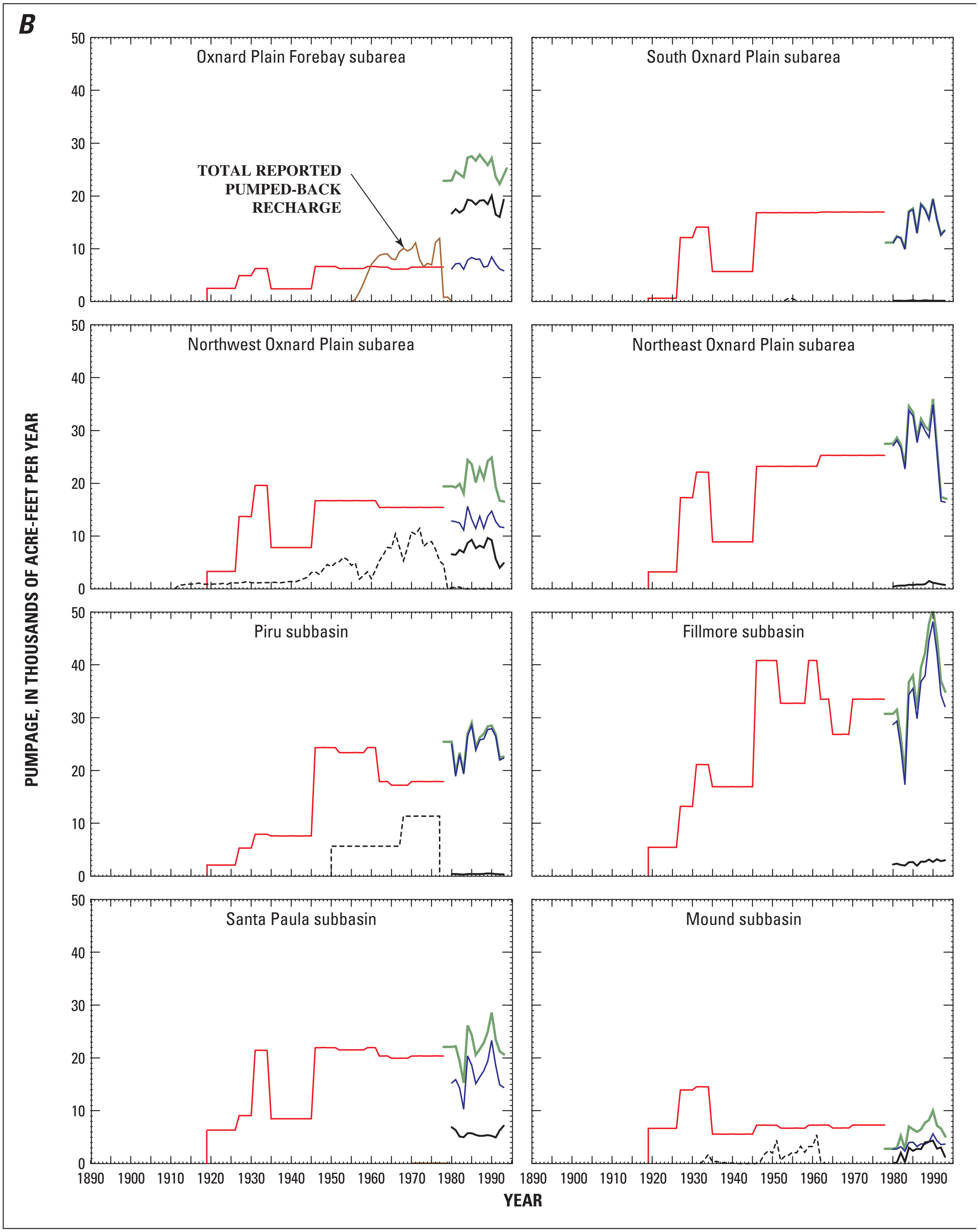

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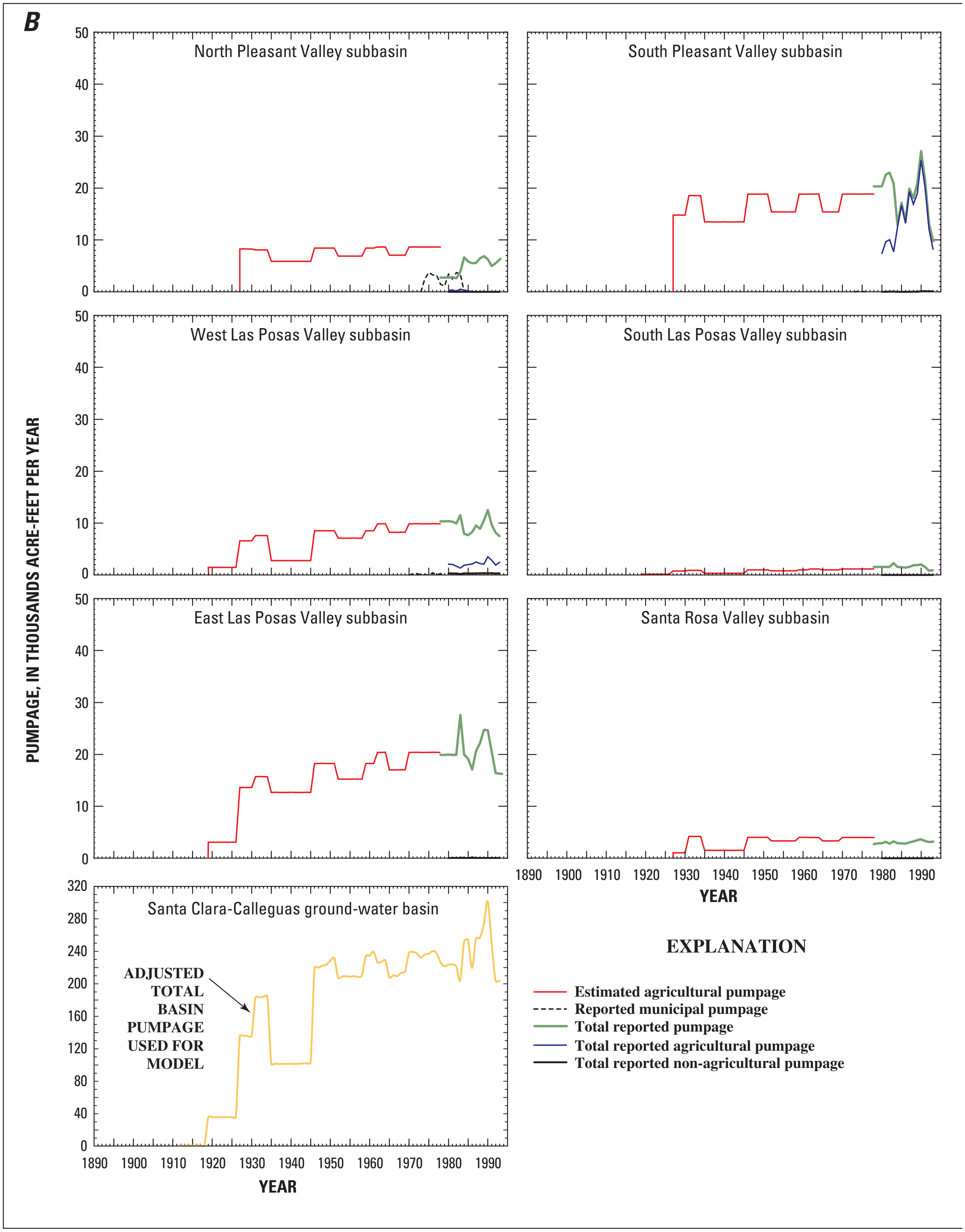

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Table 4. Summary of selected estimates of ranges and averages of direct infiltration of precipitation in subbasins in the Santa Clara–Calleguas Basin, Ventura County, California

[All estimates in acre-feet per year. Numbers in parentheses indicate the average infiltration during dry and wet periods, respectively. —, no estimate made]

Period of record in water years	Piru	Fillmore	Santa Paula	Mound	Montalvo Forebay of Oxnard Plain	Oxnard Plain	East/South Las Posas	West Las Posas	Pleasant Valley/ Santa Rosa Valley	Total bedrock recharge	Total direct infiltration recharge
[1]1894 to 1932	0–11,300 (2,700; 6,600)	0– 21,200 (4,400; 11,800)	0–11,800 (2,300; 6,600)	0–4,500 (750; 2,200)	0–8,000 (1,600; 4,500)	—	—	0–5,400 (1,000; 3,000)	—	—	400–62,200 [2](12,900; 34,800)
[3]1937 to 1951	0–11,300 (0; 4,800)	0–29,800 (0; 11,700)	0–26,200 (0; 9,600)	—	0–9,500 (0; 0)	—	—	—	—	—	—
[4]1937 to 1957	[1]200–15,100 (1,100; 5,600)	[2]500–37,900 (2,800; 13,600)	[3]0–25,600 (900; 8,000)	—	[4]100–12,200 (500; 3,200)	—	—	—	—	—	—
[5]1937 to 1967	—	—	—	—	—	—	—	—	—	—	4,000–306,400 (20,200; 108,300)
[6]1891 to 1993	950–1,900	3,100–6,200	4,500	0	1,700	3,600	800–4,700 (570; 3,400)	350–2,100	640–2,400	2,200	18,300–32,700

[1]California Department of Public Works (1934, table 59). For the Santa Clara River, the net streamflow includes estimates of runoff from ungaged tributaries and valley-floor runoff.
[2]Includes only the Santa Clara River Valley and West Las Posas subbasins.
[3]California State Water Resources Board (1956, tables 12–15).
[4]Mann and Associates (1959, plates 28–31).
[5]California Department of Water Resources (1975, tables 3, 19, and 20). For basin total, the estimated recharge from direct infiltration of precipitation includes potential runoff.
[6]Final estimates from this study for valley-floor recharge. Period of record is in calendar years.

Artificial recharge began with offstream spreading-works to help provide an adequate and dependable water supply for agriculture. Spreading-works were operated by the Santa Clara Conservation District: Santa Clara River streamflow was diverted near Saticoy beginning in 1928–29; Piru Creek streamflow was diverted near Piru beginning in 1930–31; and Santa Paula Creek streamflow was diverted near Santa Paula beginning in water year 1931 (Freeman, 1968). The initial capacities of the diversions for the Saticoy, Piru, and Santa Paula spreading grounds (fig. 4) were 120, 60, and 25 ft^3/s, respectively (Freeman, 1968). These sites represent some of the earliest efforts to divert and artificially recharge shallow ground-water aquifers. The Saticoy and Piru spreading grounds have been in continuous operation since their construction more than 70 years ago. The Santa Paula diversion was operated for about 11 years (1930–41) (fig. 11*A*), recharging a total of 26,968 acre-ft.

The UWCD added additional spreading grounds at El Rio (fig. 4) in 1955 for diversions at Saticoy and added the Pleasant Valley pipeline and reservoir in 1957 for additional storage capacity. Earthen dikes were used to divert as much as 375 ft^3/s of streamflow from the Santa Clara River at Saticoy. However, between 1955 and 1983, there were 81 dike failures at the diversion (United Water Conservation District, 1983). The earthen dike and diversion was relocated about 1 mi upstream after the riverbed degraded during the large flood of 1969, but the dike remained prone to failures at streamflows greater than 1,600 ft^3/s. A concrete dike and diversion structure, called the Freeman Diversion, was constructed in 1991. It is more durable and provides a larger diversion capacity of 460 ft^3/s. Natural streamflow during winter and spring and controlled releases of combined imported water and natural streamflow from Lake Piru during summer and fall are diverted at the Freeman Diversion. About 2,500,000 acre-ft was artificially recharged along the Santa Clara River Valley of which 378,054 acre-ft was at Piru (October 1931–December 1993), 1,228,615 acre-ft at Saticoy (October 1928–December 1993), 868,408 acre-ft at El Rio (December 1955–December 1993), and 26,968 acre-ft at Santa Paula. Some of the surface water diverted at Saticoy and later at the Freeman Diversion was directly delivered by pipelines for irrigation. About 239,966 acre-ft of the diversions was delivered directly through the Pleasant Valley pipeline (September 1958–December 1993) from surface-water diversions, and an additional 4,161 acre-ft was delivered to John Lloyd Butler farms (March 1970–May 1991) for irrigation (Greg Middleton, United Water Conservation District, written commun., 1994).

Since the 1960s, most artificial recharge at El Rio has been pumped back for nearby irrigation or delivery by pipeline to adjacent subbasins. During October 1955–December 1977, about 389,600 acre-ft was recharged at El Rio and about 170,974 acre-ft was pumped back. Net recharge during this period was about 218,600 acre-ft and the pump-back rate was 44 percent. During July 1979–December 1993, about 411,300 acre-ft was recharged and about 231,400 acre-ft (44 percent) was pumped back at El Rio. The ratio of pumpage to recharge for the El Rio artificial storage and recovery system (ASR) for 1978–93 ranged from 0.38 in wet years to 1.5 in dry years.

Irrigation Return Flow

Deep percolation of excess applied irrigation water (hereinafter referred to as “irrigation return flow”) is an additional source of artificial recharge to the ground-water system. However, areally extensive confining units retard the recharge of irrigation return flow to the upper-aquifer system throughout most of the Oxnard Plain and Mound subbasins. Irrigation return flow is redirected by drains throughout most of the southern part of the Oxnard Plain subbasin to streamflow that discharges to the Pacific Ocean through Revolon Slough (fig. 4). Increases in nitrate concentrations in ground water from wells in the upper-aquifer system (Izbicki and others, 1995; Izbicki and Martin, 1997) and related increases in ground-water levels may indicate that some irrigation return flows are infiltrating back to the upper-aquifer system in the Santa Clara River Valley and Las Posas Valley subbasins and in the Oxnard Plain Forebay and Santa Rosa Valley subbasins. The deep percolation of irrigation return flow within these subbasins consists of varying amounts of surface water and ground water. The amount of return flow was estimated based on a 70-percent irrigation efficiency of applied water (Blaney and Criddle, 1950, 1962) for the areas of irrigated agriculture estimated from five land-use maps. Estimates by Koczot (1996) were based on areas and crop types delineated from land-use maps for 1912 (Adams, 1913), 1927 (Grunsky, 1925; Koczot, 1996), 1932 (California Department of Public Works, 1934), 1950 (California Department of Public Works, 1950), and 1969 (California Department of Water Resources, 1970). The resulting annual estimates were about 17,900 acre-ft for 1912; 46,100 acre-ft for 1927; 45,700 acre-ft for 1932; 52,600 acre-ft for 1950; and 67,900 acre-ft for 1969. When the estimates for the Oxnard Plain and Mound subbasins are excluded, the annual estimates of irrigation return flow are reduced to about 11,800 acre-ft for 1912; 26,900 acre-ft for 1927; 22,400 acre-ft for 1932; 27,700 acre-ft for 1950; and 37,900 acre-ft for 1969 (Koczot, 1996).

Ground-Water Discharge

Discharge of water from the aquifer systems includes ground-water discharge as pumpage from wells, evapotranspiration along the river flood plains, and offshore flow along submarine outcrops. Some additional intermittent baseflow to rivers occurs at the subbasin boundaries, but the baseflow generally infiltrates again in the downstream subbasin and thus is not considered a loss to the ground-water flow system. During the wet periods, however, ground water discharges as stream baseflow to the Pacific Ocean; this base-flow component of discharge to the ocean was larger prior to the 1930s (Freeman, 1968).

Pumpage

The first wells were drilled on the Oxnard Plain in 1870 following the severe drought of 1853–64 and during a sustained dry climatic period (1840–83) (fig. 2). Although pumping occurred during the late 1800s and early 1900s, pumpage was minimal and therefore was not estimated for this report. These first artesian flowing wells typically were drilled to depths of 90 to 143 ft, and discharges were about 500 to 1,000 gal/min (Freeman, 1968). Many wells were completed during 1870–71 for irrigation of field crops. During the early development of the ground-water resources, the drilling of wells diminished the flow of the springs and the artesian wells. By 1912, as many as 42 pumping plants were operating north of the Santa Clara River, providing water for irrigation and domestic use (Freeman, 1968).

By 1920, a progressive lowering of water levels throughout the Santa Clara River Valley and the Oxnard Plain subbasins required the replacement of many centrifugal pumps with deep turbine pumps. By 1924, many of the previously undeveloped areas of the Santa Clara–Calleguas Basin were being used for agriculture (Grunsky, 1925). On the basis of a 1912 land-use map, estimated agricultural pumpage yields a basinwide average rate of withdrawal of about 33,500 acre-ft/yr, which results in a potential total withdrawal of about 267,700 acre-ft for the years 1919–26 of the dry-year period 1919–36 (fig. 2).

Ground water initially was developed predominantly for agricultural use. Agricultural ground-water pumpage was estimated indirectly from land-use maps for periods prior to the metering of pumpage; Koczot (1996) estimated pumpage using selected land-use maps and consumptive-use estimates for 1912, 1927, 1932, 1950, and 1969. Land-use maps were used instead of electrical power records because of the labor required to construct pumpage records for large timespans and because many wells were not powered by electricity. These land-use maps were used to delineate agricultural consumptive use which was used to estimate pumpage for periods prior to metering not represented by land-use maps. The 1912 land-use map was used for 1919–26; the 1927 map was used for 1927–30; the 1932 map was used for 1931–45; the 1950 map was used for 1946–61; and the 1969 map was used for 1962–77. These land-use time periods were based on a combination of factors including land use, climate, water levels, and historical events. The land-use pumpage estimates were used as initial agricultural pumpage for the simulation of ground-water flow but were adjusted for some periods during model calibration (fig. 11*B*). Municipal pumpage for the cities of Ventura, Camarillo, and Oxnard and for the Channel Islands Beach Community Services District (near Port Hueneme); pumpage for a fish hatchery in the southern end of the Piru subbasin; and pumpage of artificial recharge in the Oxnard Plain Forebay subbasin were estimated independently and combined with the agricultural pumpage for the total estimated pumpage prior to 1983.

Ground-water development continued to spread in the ground-water basin during the severe drought period of 1923–36, tapping deeper aquifers for agricultural supplies (fig. 2). As the surface-water resources became fully developed in the early 1930s, new ground-water development began to provide a significant proportion of the water resources. In the 1930s, the first deep wells were drilled in the Pleasant Valley and Las Posas Valley subbasins. Calculated agricultural pumpage, estimated from the 1927 land-use map, yields a basinwide average rate of withdrawal of about 128,400 acre-ft/yr for 1927 and an estimated total withdrawal of about 513,500 acre-ft for 1927–30. Calculated pumpage estimated from the 1932 land-use map is at about 174,000 acre-ft/yr, yielding an estimated total withdrawal of about 2,610,000 acre-ft for 1931–45. Estimates of agricultural pumpage, based on the 1950 land-use map, yield a basinwide average rate of pumpage of 180,000 acre-ft/yr and a total withdrawal of about 2,880,000 acre-ft for 1946–61.

By 1967, about 800 wells equipped with deep-well turbine pumps provided more than 90 percent of the water demand in the basin (Freeman, 1968). On the basis of 1969 land use, estimates of agricultural pumpage yield a basinwide average rate of withdrawal of about 201,700 acre-ft/yr, yielding an estimated total pumpage of 3,227,200 acre-ft for 1962–77.

Reported pumpage was compiled from the technical files of the FGMA and UWCD for July 1979–December 1993. These data generally were semiannual totals of user-reported agricultural, nonagricultural, and total pumpage. Early pumpage data were incomplete for the Las Posas Valley, Pleasant Valley, and Santa Rosa Valley subbasins. For these areas, 1984 FGMA reported pumpage was used to represent pumpage for 1978 through 1983. Estimated and reported total annual pumpage were combined for the entire Santa Clara–Calleguas Basin and range from 760 acre-ft for 1912 to as much as 301,400 acre-ft for 1990, which was during the last sustained drought.

Reporting of metered pumpage began in the 1980s; the total reported basinwide pumpage was 2,468,610 acre-ft during the 10-year period 1984–93 (Greg Middleton, United Water Conservation District, written commun., 1994). Of this reported total pumpage, 37 percent was from the Oxnard Plain subbasin, 37 percent from the upper Santa Clara River Valley subbasins, 13 percent from the Las Posas Valley subbasin, 9 percent from Pleasant Valley subbasin, 3 percent from the Mound subbasin, and 1 percent from the Santa Rosa Valley subbasin.

Evapotranspiration

Evapotranspiration (ET) from the regional ground-water flow system is restricted to the river flood plains, where ground water and streamflow infiltration are within the depths of the root zones of riparian vegetation. ET was not calculated for parts of the coastal areas of the Oxnard Plain subbasin where the Shallow aquifer is “semiperched.”

Previous estimates of annual ET for the Santa Clara River Valley subbasins range from 11,700 acre-ft/yr for 1892–1932 (California Department of Public Works, 1934) to 13,724 acre-ft/yr for 1958–59 (Mann and Associates, 1959). The estimated average ET for the entire Santa Rosa Valley subbasin for 1972–83 is about 4,300 acre-ft/yr (Johnson and Yoon, 1987). Previous estimates of the ET rate vary widely, ranging from 1.1 ft/yr (California Department of Water Resources, 1974a,b) to 2.4 ft/yr (California Department of Public Works, 1934) to as much as 5.2 ft/yr (Mann and Associates, 1959).

The total area classified as land with riparian vegetation or as a flood plain was estimated from the five land-use maps (1912, 1927, 1932, 1950, 1969) compiled for the RASA study (Koczot, 1996; Predmore and others, 1997). A combination of riparian land distributions from the 1912, 1927, 1932, and 1950 maps of the Conejo Creek area yields an estimated total of 14,945 acres of riparian vegetation along the stream channels for predevelopment conditions in the basin. The 1932 land-use map for the entire basin indicates a total riparian area of 11,237 acres. The most detailed set of land-use maps (1950) for the entire basin yielded a reduction to 6,539 acres of riparian land by 1950. By 1969, the total was only 2,265 acres. The model, developed for this phase of the RASA study, was used to simulate the evapotranspiration along the flood plain of the Santa Clara River, Calleguas Creek, and its major tributaries.

Coastal Flow along Submarine Outcrops

Discharge from the regional ground-water flow systems probably occurs as lateral flow to the Pacific Ocean through outcrops that are exposed along the steep walls of the submarine canyons and that truncate the submarine shelf farther offshore. Because of the alternating layers of coarse- and fine-grained sedimentary deposits in these coastal aquifer systems, submarine leakage through the tops of the upper- and lower-aquifer systems that crop out along the submarine shelf probably is small. Outside of some folklore, there are no estimates or evidence, such as cold seeps, of submarine discharge in the Ventura area. However, the possibility of seawater intrusion along the coastal Oxnard Plain subbasin has long been recognized (Grunsky, 1925; California Department of Public Works, 1934; Freeman, 1968); geochemical evidence of seawater intrusion in the upper- and lower-aquifer systems (Izbicki, 1991, 1992, 1996a) indicates a hydraulic connection to the submarine outcrops of the aquifer systems (figs. 7 and 8). Coastal flow was estimated using the ground-water flow model developed for this study and is described later in the report (see Simulation of Ground-Water Flow).

Borehole electromagnetic-induction (EM) logs of monitoring wells installed as part of the RASA Program indicate that seawater intrusion occurs along multiple coarse-grained beds that are commonly, but not exclusively, the basal units of the seven major aquifers that compose the upper- and lower-aquifer systems (figure A5.2 in Appendix 5). These basal units commonly occur above regional unconformities that are related to the major sea-level changes during the Pleistocene epoch. Natural gamma and EM geophysical logs collectively indicate that the flow of seawater from the ocean occurs laterally through the submarine outcrops and remains confined to the most transmissive coarse-grained beds that are bounded by fine-grained layers (figure A5.2 in Appendix 5). A cross-sectional solute transport model developed for the Port Hueneme area supports the conceptual framework of lateral intrusion, with vertical intrusion impeded by shallow fine-grained confining units (Nishikawa, 1997). Seawater intrusion forms a relatively sharp interface with fresh ground water as it enters the basal coarse-grained beds of the aquifer systems laterally and remains stratified in the layered coastal alluvial-aquifer systems of the Santa Clara–Calleguas Basin.

Ground-Water Levels, Movement, and Occurrence

The largest source of discharge from the ground-water flow system in the Santa Clara–Calleguas Basin is pumpage. Pumpage has caused water-levels to decline below sea level (fig. 12) which has resulted in seawater intrusion and changes in ground-water quality, altered ground-water vertical-hydraulic gradients, reduced streamflow, reduced in ET, and caused land subsidence. Long-term hydrographs of water levels in production wells (figs. 13 and 14) and in the multiple-zone observation wells (fig. 15) show fluctuations driven by multiple-year to decadal changes in recharge and seasonal to multiple-year changes in pumpage.

Upper- and Lower-Aquifer-System Water Levels

Little information exists on predevelopment water levels in the upper- or lower-aquifer system during the periods of early ground-water development. In the 1870s, wells near the coast on the Oxnard Plain subbasin were reported to deliver water to the second floor of homes under the natural artesian pressures of the Oxnard aquifer (Freeman, 1968). Several early ground-water-level maps were constructed for parts of the basin (Adams, 1913; Grunsky, 1925), but the first map of the entire basin was completed for fall 1931 (California Department of Public Works, 1934), which was during a period of agricultural development and a severe drought (1923–36, fig. 2).

As the surface-water resources became fully used in the early 1930s, ground-water development began to provide a significant part of the water resources. If the conditions in 1931 represent, in part, conditions prior to major ground-water development, then ground water in all the aquifers initially moved from the landward recharge areas toward the west or southwest to the discharge areas along the submarine outcrops offshore in the Pacific Ocean (fig. 12*A*). By the 1930s, water levels had declined as a result of the 1927–1936 drought (figs. 12*A* and 13), changing from artesian-flowing conditions of the late 1800s to below or near land surface in most wells completed in the upper-aquifer system in the Oxnard Plain subbasin (fig. 13). The effects of ground-water development and overdraft first appeared in 1931 when water levels in wells in parts of the Oxnard Plain declined below sea level (Freeman, 1968). In the 1930s, the first deep wells were drilled in the Pleasant Valley and Las Posas Valley subbasins. Before development, water levels in the lower-aquifer system probably were higher, but the water-level patterns probably were similar to the patterns shown in figure 12*A* for 1931.Well owners in coastal areas began to recognize the connection between the ground-water reservoirs and the ocean when they observed that water-level changes in wells corresponded with the rising and falling phases of the ocean tides (Freeman, 1968). The Santa Clara Water Conservation District officially recognized the linkage between overdraft and seawater intrusion in their annual report of 1931 (Freeman, 1968).

Ground-water pumpage increased during the 1940s with the widespread use of the deep turbine pump. The effects of permanent overdraft were exemplified by the lack of recovery of water levels to historical levels after the spring of 1944, which marked the end of the wettest climatic period in the 103 years of historical rainfall record at Port Hueneme (fig. 2*A*). The effects of overdraft also were recognized landward in the Santa Clara River Valley when ground-water levels declined about 20 ft in the Fillmore subbasin (fig. 14). Water levels in the southern Oxnard Plain and Pleasant Valley were below sea level by 1946 (Freeman, 1968). In 1949, water-level altitudes were 30 ft below sea level in parts of the Oxnard Plain subbasin, and one of the first wells intruded by seawater was identified along the coast in the Silver Strand well field (north of Port Hueneme) (Freeman, 1968). The direction of subsurface flow within the upper aquifers near the coast has been landward since approximately 1947 (California Department of Water Resources, 1958).

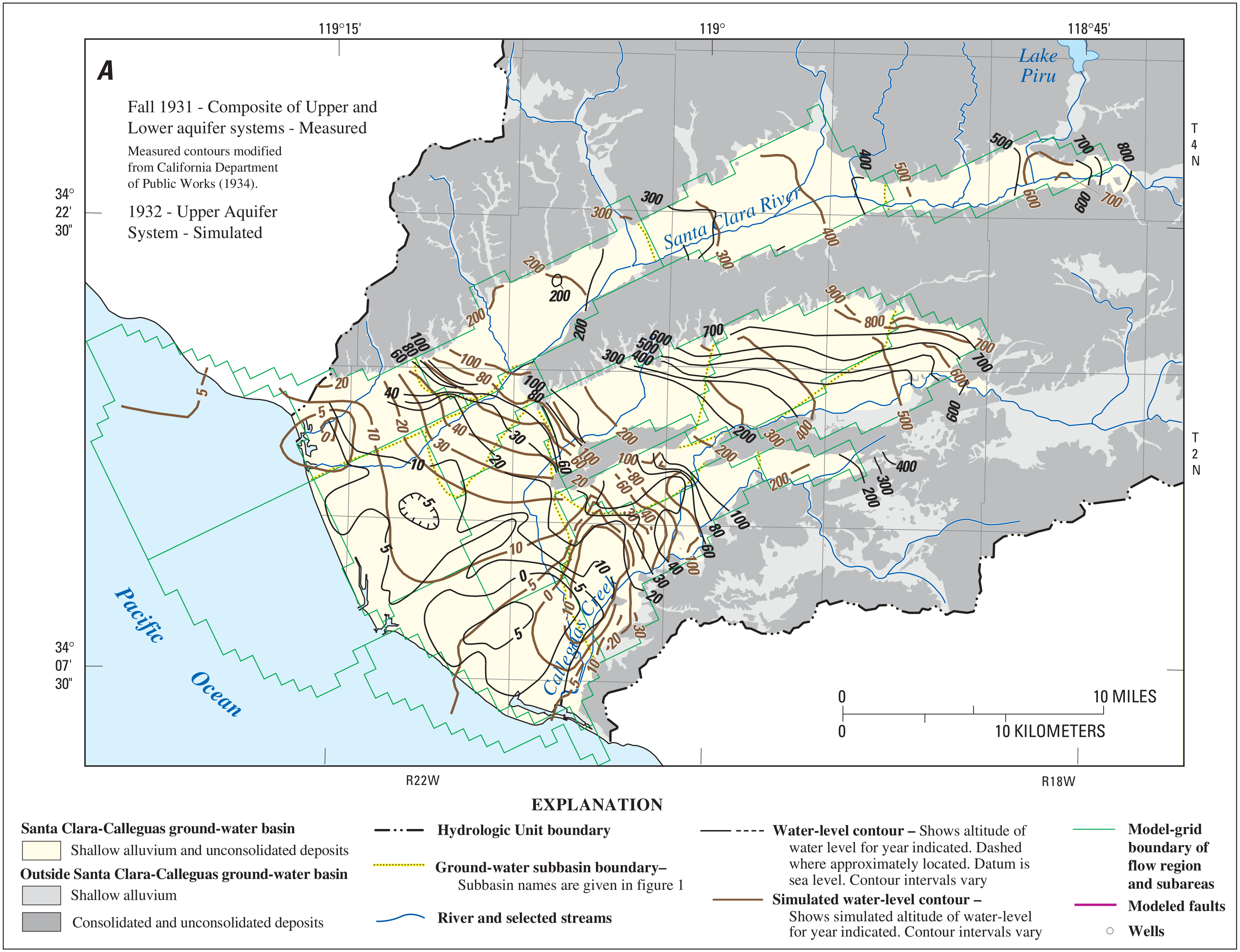
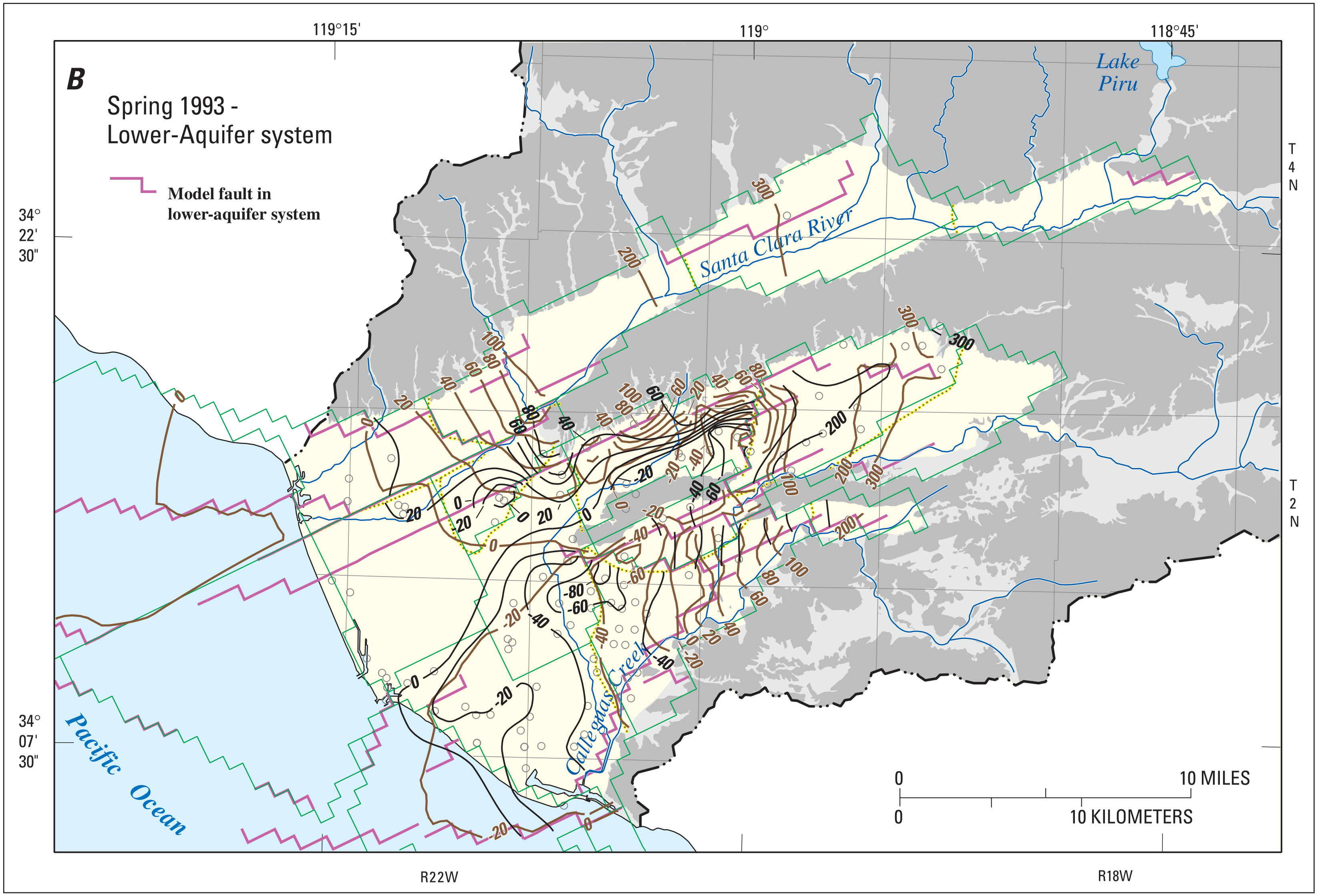


Figure 12. Ground-water level altitudes in the Santa Clara–Calleguas ground-water basin, Ventura County, California. ***A***, Fall 1932—Composite measured in upper- and lower-aquifer systems and simulated upper-aquifer system. ***B***, Spring 1993—lower-aquifer system. ***C***, Spring 1993—upper-aquifer system.



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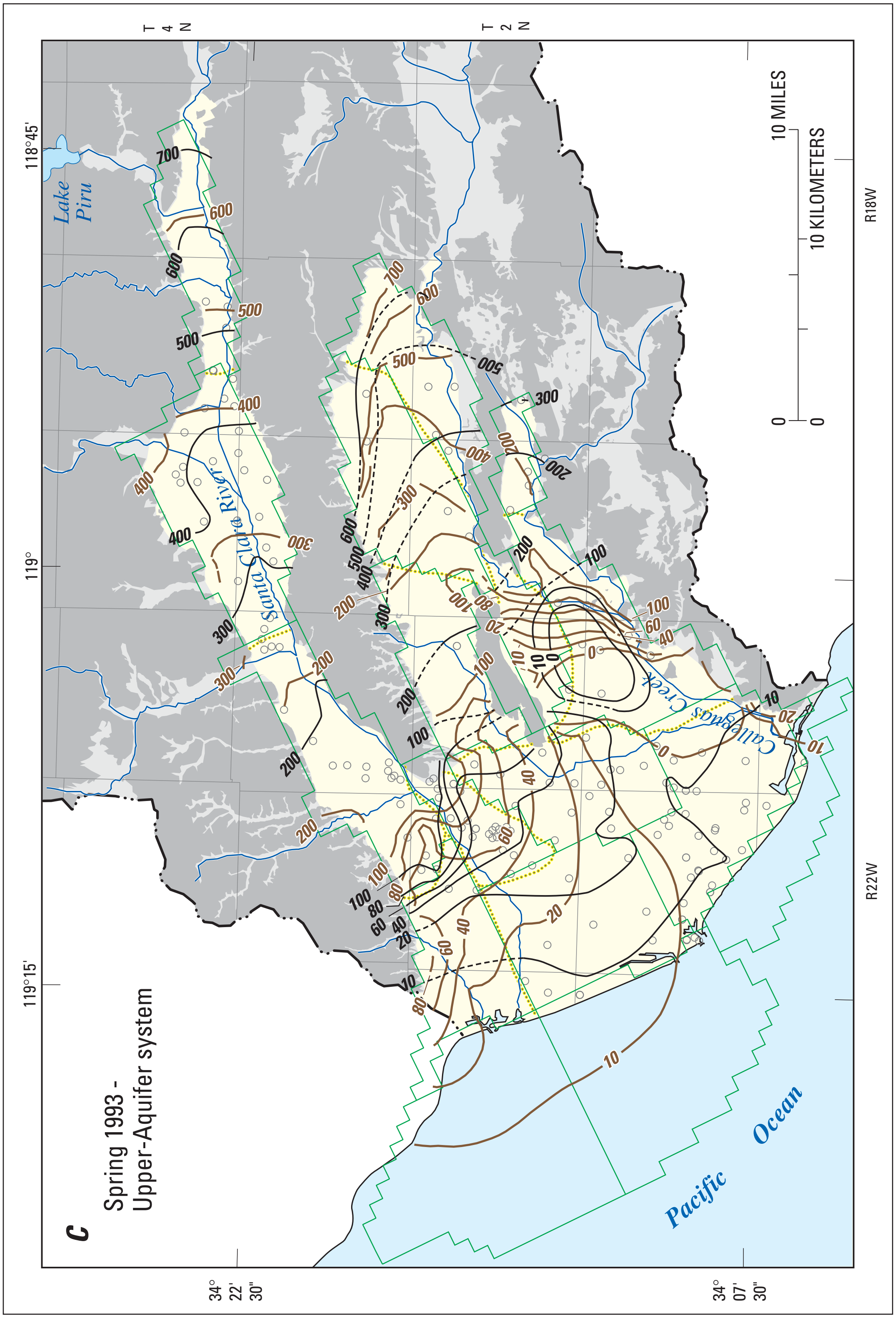

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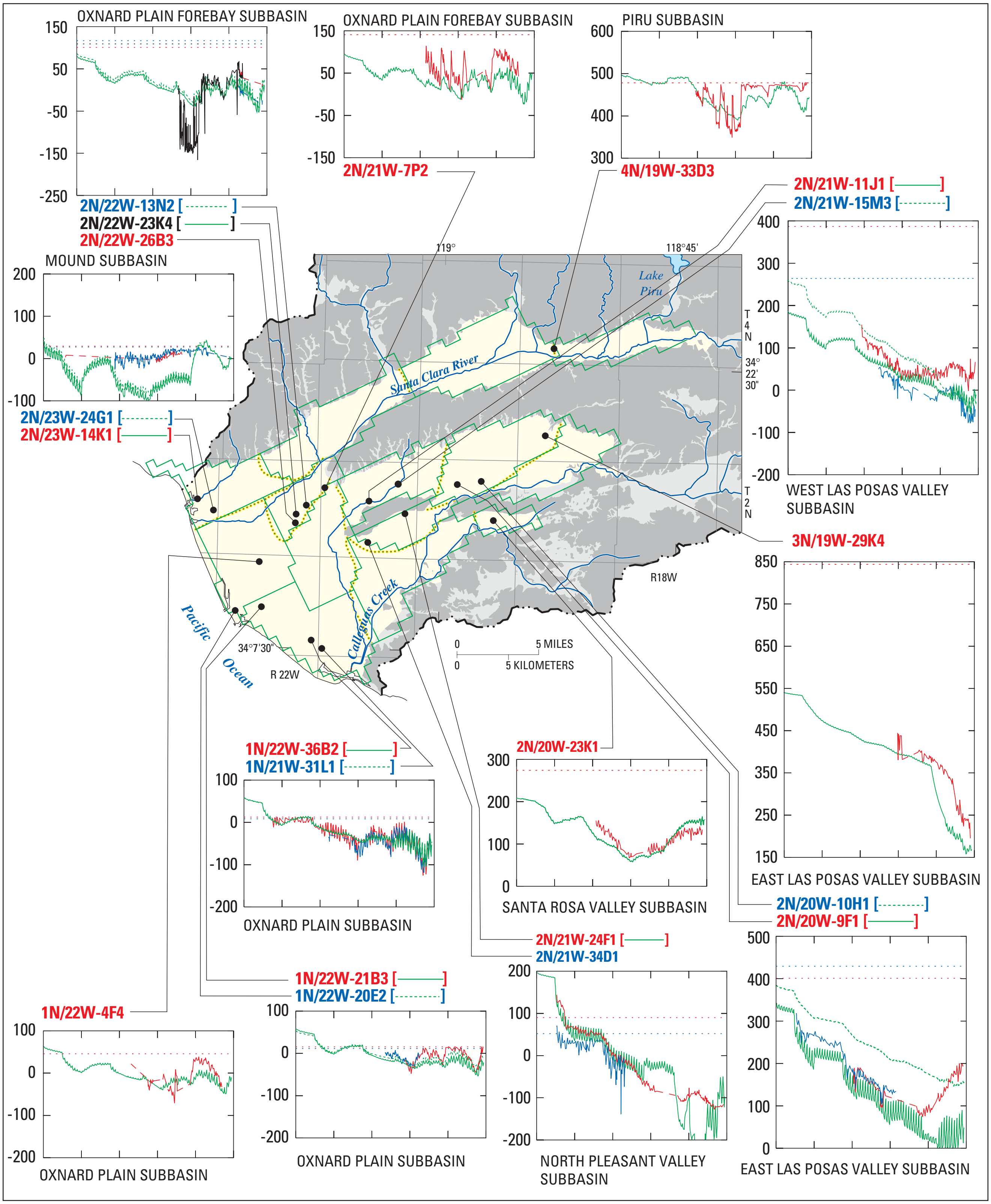


Figure 13. Measured and simulated water-level altitudes in wells completed in the lower-aquifer system of the Santa Clara–Calleguas ground-water basin, Ventura County, California.

EXPLANATION

Santa Clara-Calleguas ground-water basin

Shallow alluvium and unconsolidated deposits

Outside Santa Clara-Calleguas ground-water basin

Shallow alluvium

Consolidated and unconsolidated deposits

Hydrologic Unit boundary

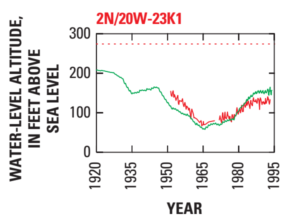
Ground-water subbasin boundary– Subbasin names are given in figure 1

River and selected streams

Landward model-grid boundary of flow region and subregions

Wells with water-level data

• Existing well (Unpublished data from California Department of Water Resources and County of Ventura Public Works Agency, written commun., 1993)



Water-level hydrograph: colored curves show water levels for the well with identification number of the same color. The water-level curves are dashed when the time between measurements exceeds one year. The dotted line in the corresponding color represents the land-surface altitude at the well site. Green curves are simulated water levels in lower-aquifer system. See figure 1 for locations of subbasins.

Figure 13—Continued.

When ground-water pumpage approached recorded maximum levels in 1951, which was at the end of a drought, water-level declines reached a new historical low in the upper-aquifer system (fig. 14) and levels began to decline significantly in the lower-aquifer system in the Oxnard Plain subbasin (fig. 13). By 1950, water levels had declined below sea level in the lower-aquifer system as far inland as the Pleasant Valley subbasin (fig. 13). Through 1950, water levels in most wells completed in the lower-aquifer system remained near land surface (fig. 13). Water levels in wells in the West and South Las Posas Valley subbasins indicate a water-level recovery in the upper-aquifer system beginning in the 1950s (fig. 14) related to increased irrigation return flow along Arroyo Simi and Beardsley Wash, importation of water which reduced local pumpage, discharge of pumped ground water into Arroyo Simi to control shallow ground-water levels, and discharge of treated municipal sewage into Arroyo Las Posas.

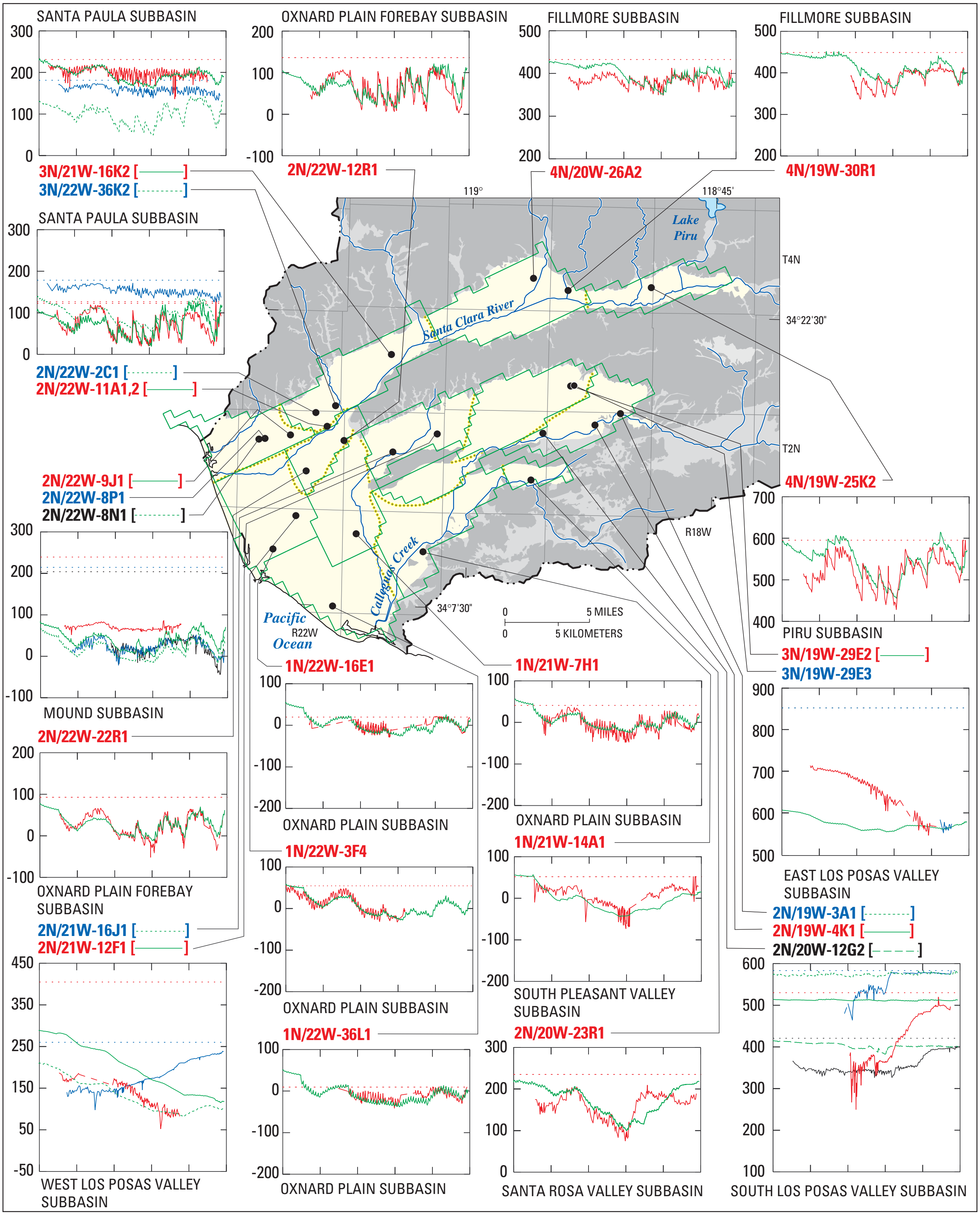


Figure 14. Measured and simulated water-level altitudes in wells completed in the upper-aquifer system of the Santa Clara–Calleguas ground-water basin, Ventura County, California.

EXPLANATION

Santa Clara-Calleguas ground-water basin

Shallow alluvium and unconsolidated deposits

Outside Santa Clara-Calleguas ground-water basin

Shallow alluvium

Consolidated and unconsolidated deposits

Hydrologic Unit boundary

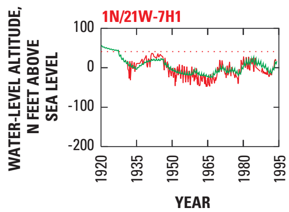
Ground-water subbasin boundary– Subbasin names are given in figure 1

River and selected streams

Landward model-grid boundary of flow region and subregions

Wells with water-level data

● Existing well (Unpublished data from California Department of Water Resources and County of Ventura Public Works Agency, written commun., 1993)



Water-level hydrograph: colored curves show water levels for the well with identification number of the same color. The water-level curves are dashed when the time between measurements exceeds one year. The dotted line in the corresponding color represents the land-surface altitude at the well site. Green curves are simulated water levels in upper-aquifer system. See figure 1 for locations of subbasins.

Figure 14—Continued,

The lowering of water levels continued in the upper- and lower-aquifer systems in the Oxnard Plain subbasin through the next dry period, 1959–64, furthering seawater intrusion (figs. 13 and 14). Water-level hydrographs (fig. 13) for many wells in the lower-aquifer system in the North Pleasant Valley and the Las Posas Valley subbasins indicate a monotonic decline through the 1950s and 1960s. Water levels started to recover in the Santa Rosa Valley subbasin beginning around 1965 because of decreased pumpage in the upper- and lower-aquifer systems and discharge of treated municipal sewage into Conejo Creek (figs. 13 and 14). The hydrographs of wells in the Mound subbasin and wells near the Hueneme submarine canyon (figs. 13 and 14) show little to no additional decline during these decades. By the late 1960s, thousands of acres of aquifer had been intruded by seawater in the Port Hueneme and Point Mugu areas, and coastal farmland had been lowered by land subsidence (see “Land Subsidence Effects”) owing to several decades of sustained overdraft.

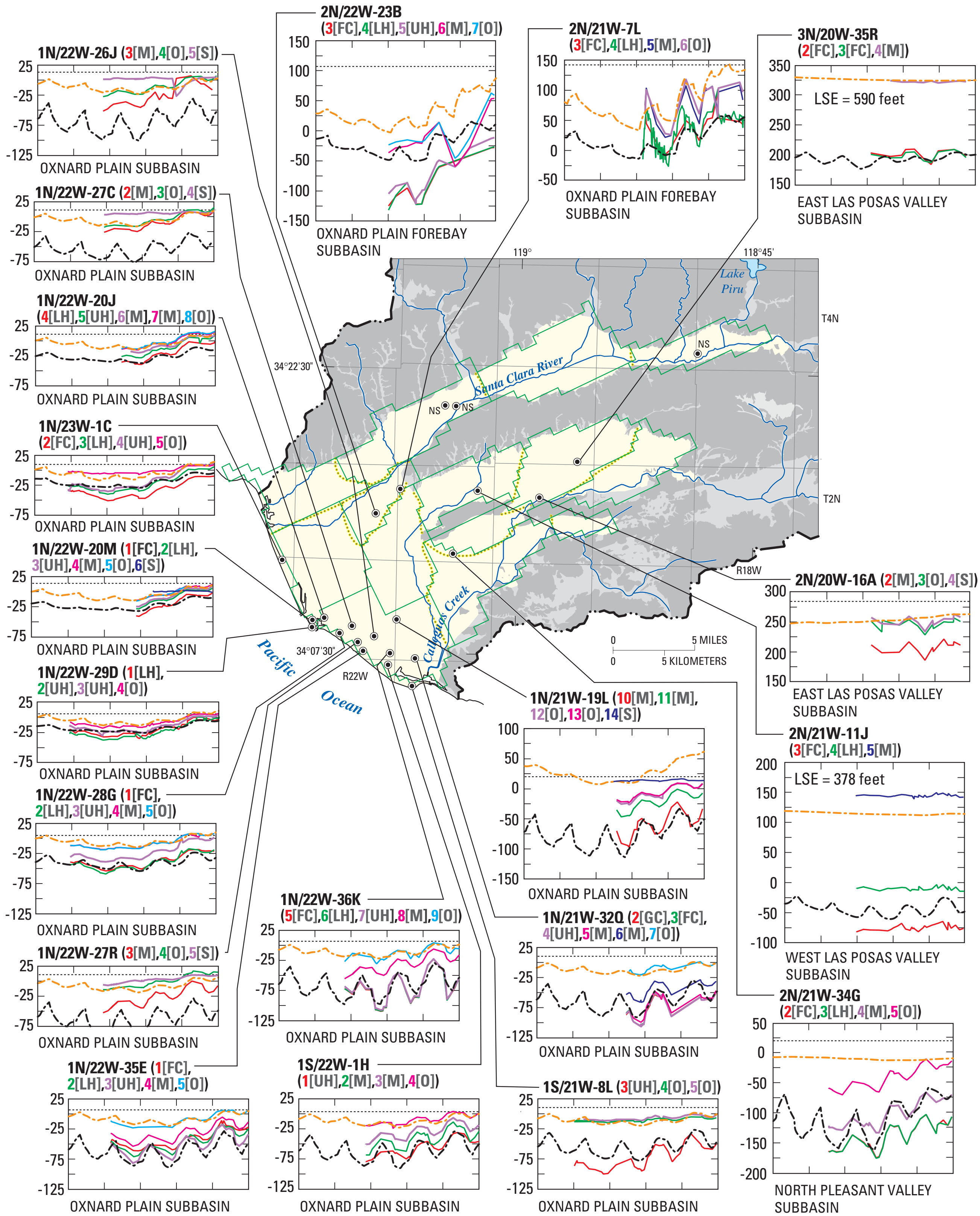


Figure 15. Measured and simulated water-level altitudes at sites with multiple wells of different depths completed in the Santa Clara–Calleguas ground-water basin, Ventura County, California.

EXPLANATION

Santa Clara-Calleguas ground-water basin

Shallow alluvium and unconsolidated deposits

Outside Santa Clara-Calleguas ground-water basin

Shallow alluvium

Consolidated and unconsolidated deposits

Hydrologic Unit boundary

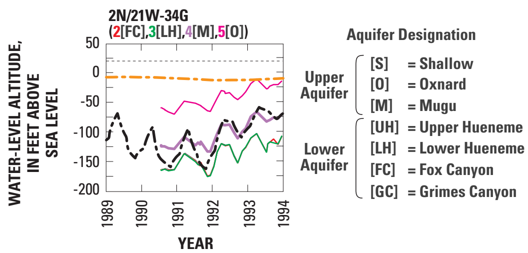
Ground-water subbasin boundary– Subbasin names are given in figure 1

River and selected streams

Landward model-grid boundary of flow region and subregions

Well and data -

Multiple-well site sampled as a part of this study. (Densmore, 1996)
NS, indicates that data is not shown.



Water-level hydrograph and well number with colored curves showing water levels for the well with sequence number of the same color. The water-level curves are dashed when the time between measurements exceeds one year. Letters in brackets are aquifer designations. The dotted line, when shown, represents the land-surface altitude (LSA) at the multiple-well site. Dashed orange curve is simulated water levels in upper-aquifer system (layer 1) and dashed black curve is simulated water levels in lower-aquifer system (layer 2).

Figure 15—Continued.

Water levels in both aquifer systems in the Oxnard Plain subbasin partially recovered in the late 1960s owing to increased artificial recharge in the Oxnard Plain Forebay subbasin and natural recharge owing to a wetter climate. The water levels from wells in the upper-aquifer system in the Santa Clara River Valley subbasins also showed recovery during the late 1960s and early 1970s. The absence of wells completed in the lower-aquifer system in the upper Santa Clara River Valley subbasins precluded an assessment of the history or distribution of water levels there. Data from wells in the East Las Posas Valley subbasin indicate that water-levels began to recover in the late 1970s. This recovery was related to importation of water that reduced local pumpage, discharge of pumped ground water into Arroyo Simi to control shallow ground-water levels, and discharge of sewage effluent into Arroyo Las Posas. Similar water-level recoveries in the Santa Rosa Valley subbasin began in about 1965 (figs. 13 and 14) owing to decreased pumpage and discharge of sewage effluent into Conejo Creek and some water-level recovery near stream channels in shallower wells.

By the end of the most recent drought (1987–91), water levels were below sea level throughout the Oxnard Plain, Mound, and Pleasant Valley subbasins in both aquifer systems and below sea level in the lower-aquifer system throughout the West Las Posas Valley subbasin. In the inland subbasins, such as the South Pleasant Valley and West Las Posas Valley subbasins, water levels in many of the wells were near the historical lows in 1991 (figs. 13 and 14).

Beginning in 1992, which is the start of the most recent wet period, there was an increase in recharge owing to, in part, the increased capacity for artificial recharge at the Freeman Diversion and to a temporary reduction of pumpage from the coastal subbasins owing to increased surface-water supplies through pipeline deliveries, conservation practices, and new irrigation technology that increased irrigation efficiency. Pumpage was reduced because of a drilling moratorium established by the FGMA in 1983 on new wells completed in the upper-aquifer system in the Oxnard Plain. A comparison of the water-level maps for 1931 and 1993 indicates that by 1993 water levels had recovered in the upper-aquifer system and were greater than levels in 1931 (fig. 12*A*,*C*). Water levels in 1993 were about 5 ft higher near the coast, more than 20 ft higher in the Oxnard Plain Forebay than the 1931 levels, and above sea level throughout most of the Oxnard Plain. The water-level map for the lower-aquifer system shows that water levels were below sea level in the South Oxnard Plain subarea and Pleasant Valley subbasins (fig. 12*B*). Water-level data were not available for other inland subbasins for 1931; however, the hydrographs of long-term water levels indicate subdued fluctuations, or decline and recovery cycles (fig. 14), that may indicate that the shallower parts of the upper-aquifer system in these ground-water subbasins had recharged owing to increased streamflow during wet periods or increased discharge of treated sewage effluent.

Water-Level Differences Between Aquifers

Differences in water levels occur between the different aquifers (fig. 15) in the Santa Clara–Calleguas Basin. The water levels in the coastal Oxnard aquifer are lower than the water levels in the Shallow aquifer during dry-year periods and become higher than the water levels in the Shallow aquifer during recoveries (fig. 15) in wet-year periods. Large water-level differences occur between the Shallow and the underlying aquifers during the irrigation season, especially within the South Oxnard Plain subarea. These differences are primarily due to thick deposits of silt and clay in the Shallow aquifer that retard the movement of ground water between the Shallow and the Oxnard aquifers. Water levels for the RASA monitoring wells completed in the Shallow aquifer show little seasonal change owing to ground-water pumping or precipitation (fig. 15). Other shallow wells in the northern part of the Oxnard Plain subbasin show rises that are related to precipitation and declines that may be related to leakage (Neuman and Gardner, 1989, figs. 2 and 3). Previous investigators estimated that vertical leakage from the shallow semiperched system to the Oxnard aquifer ranges from 6,000 acre-ft/yr (California Department of Water Resources, 1971) to 20,000 acre-ft/yr (Mann and Associates, 1959).

Similarly, wells with depths of less than 50 ft completed in the Santa Clara River Valley subbasins also have higher water levels than those of nearby wells completed deeper in the upper-aquifer system. These elevated water levels may indicate some degree of hydraulic separation between the Shallow (recent alluvium) aquifer and the underlying aquifer along the Santa Clara River.

Except for those wells tapping the Shallow aquifer, water levels in wells in the coastal subareas and Santa Clara Valley subbasins indicate spring and summer declines followed by recovery during late fall and winter of each year. The seasonal fluctuations in wells in the upper-aquifer system are comparable with the changes in the wells in the lower-aquifer system north of the Hueneme submarine canyon. In the Oxnard Plain subbasin south of the Hueneme submarine canyon and in the Pleasant Valley subbasin, seasonal fluctuations in water levels are greater in the lower-aquifer system than in the upper-aquifer system. The smaller water-level differences and seasonal fluctuations near Port Hueneme are partly due to the source of water (seawater intrusion) along the near-shore submarine canyon outcrops, which tends to subdue the water-level fluctuations and changes in water levels between aquifers. In contrast, the larger water-level differences near Point Mugu are, in part, due to offshore faulting, which creates a barrier to ocean inflow for the lower-aquifer system. However, wells completed in the Mugu aquifer have water-level fluctuations that are similar to those of the lower-aquifer system. The similarity in seasonal fluctuations in the Mugu aquifer and the lower-aquifer system, in part, may be due to well-construction practices; well screens typically span the Mugu aquifer and parts of the lower-system aquifers. Flowmeter logs of wells screened opposite both the Mugu aquifer and the lower-aquifer system indicate a significant contribution from the Mugu aquifer (table 5). Water levels in the Pleasant Valley subbasin are about 50 ft lower in the Mugu-equivalent aquifer than water levels in the Oxnard-equivalent aquifer. This sustained water-level difference, along with water-level responses measured during short-term aquifer tests (Hanson and Nishikawa, 1996) and geophysical data (Densmore, 1996; Appendix 6), indicates that these aquifers are separated by fine-grained confining beds. The difference in water levels between the Oxnard aquifer and the lower-aquifer system increases during periods of pumping and decreases during seasonal periods of recovery.

Water levels in the lower-aquifer system were consistently more than 100 ft lower than water levels in the upper-aquifer system in the inland subbasins of Pleasant Valley, West Las Posas Valley, and East Las Posas Valley. For the inland Santa Clara River Valley subbasins, water-level differences in the Piru and Santa Paula subbasins were 10 to 25 ft lower for water levels in the lower-aquifer system than for levels in the upper-aquifer system.

Inter-Aquifer Flow

Flow between aquifers can be an important consideration in the management of water resources. Vertical water-level differences (figs. 13–15) indicate the potential for upward and downward flow between aquifers and aquifer systems. However, these differences can result in appreciable leakage only if a conductive pathway is present. Vertical flow between aquifers can occur as leakage through coarse-grained sedimentary layers, through and around fine-grained layers, and as vertical flow in and around well bores.

Vertical flow between the semiperched and the upper-aquifer systems also can occur through failed and abandoned wells (Stamos and others, 1992). Estimates of the number of abandoned and potentially failed wells range from 167 (Predmore, 1993) to 238 (Ventura County Resource Management Agency, Environmental Health Department, 1980) in the Oxnard Plain and as many as 1,215 wells throughout Ventura County (Predmore, 1993). Wellbore heat-pulse flowmeter tests in selected wells in the Oxnard Plain subbasin indicate that intraborehole flow rates of 3 to 11 gal/min may occur in some failed wells. This suggests a total maximum leakage of about 800 to 4,220 acre-ft/yr for periods when the hydraulic gradients are downward. The hydrographs for the multiple-observation well sites show that the heads in producing aquifers can vary seasonally and climatically (fig. 15). Thus, during wet-year periods or during periods of reduced pumpage, heads in the aquifer system can result in intraborehole discharge from the ground-water flow system to the overlying semiperched systems. Conversely, during dry-year periods or in areas of increased pumpage, heads in the semiperched system could be greater than heads in the underlying aquifers and could result in leakage as recharge to the ground-water system. For example, wellbore leakage of as much as 11 gal/min was measured with a heat-pulse flowmeter in failed monitoring well 1N/22W-27R2. However, detailed chemical sampling at nearby multiple-completion monitoring wells 1N/22W-27R3–5 (Izbicki, 1996a) indicates that the effects of this wellbore leakage were not areally extensive.

Vertical flow also can occur from the underlying marine sedimentary rocks or from brines related to oil deposits. Methane is reported to discharge from some production wells that are completed to depths just above the oil fields just west of Pleasant Valley in the Oxnard Plain subbasin (fig. 9). Geochemical data indicate that the amounts of leakage from deeper and older formations in the southern part of the Oxnard Plain and South Pleasant Valley subbasins probably are small (Izbicki, 1991, 1996a, figs. 3 and 5).

Source of Water to Wells

The relative contribution of water to wells completed in multiple aquifer systems is dependent on the local stratigraphy and on well construction. The vertical distribution of ground-water withdrawals from wells was estimated from flowmeter logs of 17 wells completed as part of the RASA Program and other studies (table 5, fig. 17*B* presented later in the "Model Boundaries" section, figure A5.1 in Appendix 5). Where wells are perforated across younger aquifers and older aquifers, most of the water is produced from the more transmissive younger aquifers [table 5, figure A5.1 in Appendix 5]. Combined with the stratigraphy, flowmeter logs indicate that the most productive and areally extensive water-bearing zones commonly occur as basal coarse-grained layers that overlie major regional unconformities. However, the relative contribution to any particular well from less productive aquifers may increase with increased pumping rates and decreased water levels in the more productive aquifers (table 5).

The most important aspects of well construction are the vertical extent of the well screen and the depth and location of the pump intake relative to the well screen. Wells that are screened across the basal layer of the upper-aquifer system can derive as much as 70 percent of the wellbore inflow from this relatively thin layer. Wells that are completed only in the lower-aquifer system can derive 100 percent of the wellbore inflow from the basal coarse-grained layer in the Hueneme aquifer (table 5). Flowmeter logs are not yet available for wells throughout most of the Oxnard Plain and Las Posas Valley subbasins; for wells in all the Piru, Fillmore, and Santa Rosa Valley subbasins; and for wells screened only in the upper-aquifer system.

Source, Movement, and Age of Ground Water

The source, movement, and age of ground water in the Santa Clara–Calleguas Basin can be inferred from the isotopic content of ground-water and surface-water samples. Based on deuterium isotope samples, most of the water in the upper- and lower-aquifer systems is derived from streamflow infiltration of high-altitude precipitation along the Santa Clara River that originated largely as runoff of precipitation falling at the higher altitudes of the surrounding mountains (Izbicki, 1996b, fig. 3). Isotopic data also suggest a local contribution of mountain-front recharge and direct infiltration of locally derived precipitation in the Las Posas and Pleasant Valleys and along the margins of the Santa Clara River Valley (Izbicki, 1996b). Although a large component of irrigation return flow may contribute to infiltration, no large areas of the Oxnard aquifer in the Oxnard Plain had an isotopic signature similar to that of evaporated waters. Analysis of ground-water samples for the hydrogen isotope tritium indicates that recent recharge (since 1952) has occurred largely in the Santa Clara River Valley subbasin, the Oxnard Plain Forebay subbasin, the northwestern part of the Oxnard Plain subbasin, and the South Las Posas Valley subbasin (Izbicki, 1996b, fig. 5). Tritium data also indicate that the artificial recharge from the Oxnard Plain Forebay subbasin has largely infiltrated the upper-aquifer system. Ages determined by carbon-14 analysis of ground-water samples indicate that water in the upper-aquifer system directly beneath the Saticoy spreading grounds is relatively young (less than 500 years old), but water in the lower-aquifer system beneath the El Rio spreading grounds ranges from 700 to more than 13,000 years old (Izbicki, 1996b, fig. 6). Samples from the lower-aquifer system near the coast range from about 7,000 to 23,000 years old (Izbicki, 1996b, fig. 6). Samples from wells in the Las Posas Valley and Pleasant Valley subbasins yielded ages of about 700 to 6,000 years old (Izbicki, 1996b, fig. 7). Collectively, these data indicate that the upper-aquifer system is recharged by streamflow infiltration and mountain-front recharge; the lower-aquifer system has received little recent water; and ground water moved relatively slowly under the hydraulic gradients present prior to water development.

Table 5. Summary of well-construction data and discharge rates and inflows from flowmeter logs of wells in selected subbasins of the Santa Clara–Calleguas Basin, Ventura County, California

[State well No.: See well-numbering diagram in text. Total depth of well and depth to top and bottom of well screen in feet below land surface. —, no data]

State well No.	Local well name	Subbasin	Total drilled depth (feet)	Well casing diameter (inches)	Depth to top of well screen (feet)	Depth to bottom of well screen (feet)	Year of flowmeter log	Well-test discharge rate (gal/min)	Inflow	
									Percent from upper/lower aquifer systems	Percent from Oxnard/Mugu/Hueneme/Fox Canyon/Grimes Canyon system
1N/21W-3K1	PVCWD-WELL#04	South Pleasant Valley	1,453	18	403	1,433	1980[1]	1,000	17/83	—/17/3/17/63
							1991	1500	30/70	—/30/21/11/38
1N/21W-3R1	PVCWD-WELL#01	South Pleasant Valley	1,033	18	443	1,013	1980[1]	4,000	9/91	—/9/91/0/—
							1991	1,414	54/46	—/54/46/0/—
1N/21W-4D4	PVCWD-WELL#03	Oxnard Plain	1,341	18	571	1,321	1980[1]	2,000	—/100	—/—/5/36/59
							1991	1,168	—/100	—/—/19/26/55
1N/21W-4K1	PVCWD-WELL#05	South Pleasant Valley	1,240	18	400	1,220	1980[1]	2,000	4/96	—/4/5/60/31
1N/21W-8R1	PVCWD-WELL#07	Oxnard Plain	1,383	18	603	1,363	1980[1]	2,500	—/100	—/—/0/28/72
							1991	1,128	—/100	—/—/0/21/79
1N/21W-10G1	PVCWD-WELL#06	South Pleasant Valley	1,020	18	420	1,000	1979[1]	3,150	—/100	—/—/34/53/0
							1992	2,000	—/100	—/10/27/37/26
1N/21W-15D2	PVCWD-WELL#08	South Pleasant Valley	1,103	18	383	1,083	1980[1]	4,000	17/83	—/17/20/58/5
							1991	1,121	40/60	—/40/30/23/7
1N/21W-21H2	PVCWD-WELL#10	South Pleasant Valley	883	18	503	863	1980[1]	2,500	—/100	—/—/49/51/—
1N/21W-22C1	PVCWD-WELL#09	South Pleasant Valley	1,023	18	443	1,003	1980[1]	4,000	—/100	—/—/25/53/22
							1991	1,440	—/100	—/—/19/37/44
1N/21W-28D1	PVCWD-WELL#11	Oxnard Plain	960	9	463	923	1980[1]	2,000	—/100	—/—/58/42/—
							1991	1,100	—/100	—/—/100/0/—
1N/21W-31L1	PTMUGU#03	Oxnard Plain	702	12	350	700	1991	407	12/88	—/12/88/—/—
1N/22W-3F5	OXNARD#20	Oxnard Plain	1,126	18	526	1,106	1984[2]	2,000	—/100	—/—/71/29/—

Table 5. Summary of well-construction data and discharge rates and inflows from flowmeter logs of wells in selected subbasins of the Santa Clara–Calleguas Basin, Ventura County, California—Continued

State well No.	Local well name	Subbasin	Total drilled depth (feet)	Well casing diameter (inches)	Depth to top of well screen (feet)	Depth to bottom of well screen (feet)	Year of flowmeter log	Well-test discharge rate (gal/min)	Inflow: Percent from upper/lower aquifer systems	Inflow: Percent from Oxnard/Mugu/Hueneme/Fox Canyon/Grimes Canyon system
2N/20W-20M5	SAINT JOHNS#6	North Pleasant Valley	700	18	480	700	1992[3]	500	—/100	—/—/58/42/—
							1992[3]	1,000	—/100	—/—/58/42/—
							1992[3]	1,500	—/100	—/—/53/47/—
2N/21W-34G1	PVCWD-WELL#02	South Pleasant Valley	1,483	18	403	1,463	1980[1]	4,000	—/100	—/—/25/75/0
							1992	2,065	—/100	—/—/25/67/8
							1993	2,065	—/100	—/—/18/68/14
2N/22W-8F1	VICTORIA-WELL#2	Mound	1,190	18	580	1,180	1994[4]	1,906	50/50	—/50/50/—/—
							1994	2,485	44/56	—/44/56/—/—
							1994	4,015	33/67	—/33/67/—/—
2N/22W-13N2	ELRIO#12	Oxnard Forebay	1,112	18	752	1,092	1983[5]	1,960	—/100	—/—/100/—/—
3N/21W-11J5	SANTA PAULA#12	Santa Paula	700	16	260	700	1991	1,000	100/0	—/100/0/—/—
							1991	1,500	73/27	—/73/27/—/—
							1991	2,500	72/28	—/72/28/—/—

[1]Data from Pleasant Valley Water Conservation District (Lee Miller, written commun.,1991).
[2]Data from Geotechnical Consultants, Inc. (Ted Power, written commun, 1992).
[3]Data from Fugro-McClelland, Inc. (David Gardner, written commun., 1993).
[4]Data from Fugro-McClelland, Inc. (Curtiss Hopkins, written commun., 1994).
[5]Data from United Water Conservation District (Jim Gross, written commun., 1991).

Land-Subsidence Effects

Ground-water withdrawals, oil and gas production, and tectonic movement are three potential causes of land subsidence in the Oxnard Plain and adjacent subbasins (fig. 9) (Hanson, 1995). Ground-water levels in the Oxnard Plain subbasin have declined steadily since the first wells were completed in the 1870s. Ground water, however, has remained a primary source of water since the early 1900s. Oil and gas has been produced in the Santa Clara–Calleguas Basin since the 1920s and in the Oxnard Plain subbasin since the 1940s. The basin is a part of the tectonically active Transverse Ranges physiographic province. Ventura County has delineated a probable subsidence-hazard zone that includes parts of the Piru, Fillmore, Santa Paula, Mound, Oxnard Plain Forebay, Oxnard Plain, and Pleasant Valley subbasins (Ventura County Board of Supervisors, 1988).

Since the early 1900s, water-level declines in the upper- and lower-aquifer systems in the Oxnard Plain subbasin have ranged from about 50 to 100 ft. Water levels in wells at the multiple-well monitoring sites are lower in the lower-aquifer system than in the upper-aquifer system—by 20 ft near the Hueneme submarine canyon along the central coast and by about 80 ft near the Mugu submarine canyon along the southern coast of the Oxnard Plain subbasin. Because early pumpage data are unavailable for the Oxnard Plain subbasin, the total quantity of water withdrawn is unknown. However, reported pumpage data indicate that during 1979–91 about 822,000 acre-ft of ground water was withdrawn from the Oxnard Plain subbasin at a relatively constant rate. This pumpage has resulted in water-level declines that, in turn, have increased the effective stress on the aquifer-system sediments. An increase in the effective stress on aquifer sediments beyond their preconsolidation stress results in compaction and reduction of pore space and mechanically squeezes water from sediments.

More than 7,900 acre-ft of brines, 8,000 acre-ft of oil, and 72 million cubic feet of natural gas were withdrawn from oilfields in the Oxnard Plain subbasin (fig. 9) between 1943 and 1991 (Steven Fields, Operations Engineer, California Department of Conservation, Division of Oil and Gas, written commun., 1992). Pressure declines equivalent to more than 1,100 ft of water-level decline have occurred in the Oxnard oilfields since the onset of oil and gas production. These declines alone could potentially account for local subsidence of 1.5 to 2.0 ft (California Division of Oil and Gas, 1977).

Tectonic activity in the form of plate convergence and north-south crustal shortening has resulted in an average regional horizontal movement in the subbasins north of the Oxnard Plain of about 0.007 ft/yr over the past 200,000 years (Yeats, 1983). Vertical movement, as uplift north of the Oxnard Plain subbasin and as subsidence in the Oxnard Plain subbasin, has been caused by plate convergence and related earthquakes throughout the basin. For the southern edge of the Oxnard Plain subbasin (fig. 9*A*), elevation data from bench marks (BM) on bedrock (for example, BM Z 583) indicate that the 0.17 ft of subsidence that occurred during 1939–78 (at a rate of about 0.004 ft/yr) may be related to tectonic activity.

Data from a coastal leveling traverse near the southeastern edge of the Oxnard Plain (fig. 9*A*,*B*) indicate that as much as 1.6 ft of subsidence occurred during 1939–60 at BM E 584 (0.07 ft/yr) and an additional 1 ft occurred during 1960–78 (0.06 ft/yr). During 1960–92, 0.5 ft of subsidence (0.02 ft/yr) was measured at BM Z 901, which is southwest of BM E 584 and at the edge of the coastal Oxnard Plain. Bench-mark trajectories (fig. 9*C*) indicate that subsidence continues and may be driven by extreme water-level declines that occur during drought periods. Farther inland, where water-level and oilfield pressure declines are largest, greater subsidence might be expected.