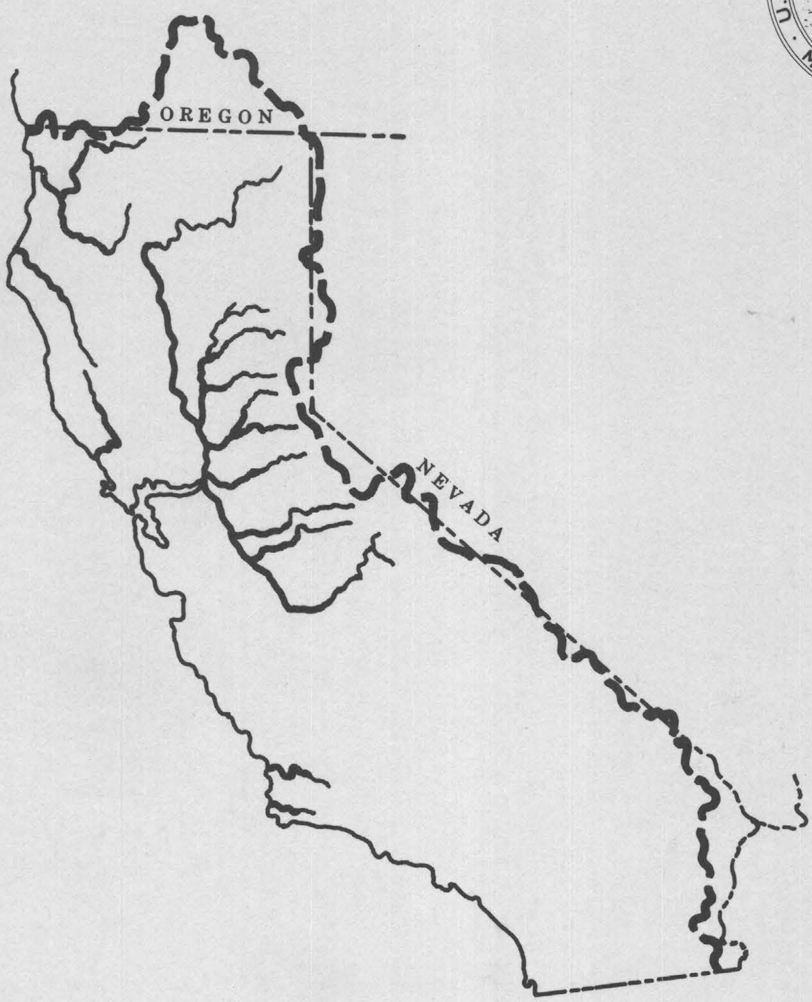
Summary Appraisals of the Nation's Ground-Water Resources—California Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-E



Summary Appraisals of the Nation's Ground-Water Resources—California Region

By H. E. THOMAS *and* D. A. PHOENIX

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-E

Problems and opportunities related to the use of ground water in highly diverse hydrologic and social environments

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data

Thomas, Harold Edgar, 1906-
Summary appraisals of the Nation's ground-water resources–California region.

(Geological Survey Professional Paper 813-E)
Bibliography: p. 49-51.
Supt. of Docs. no.: I 19.16:813-E
1. Water, Underground–California. 2. Water, Underground–The West. 3. Water-supply–California. 4. Water-supply–The West.
I. Phoenix, David A., 1916- joint author. II. Title. III. Series: United States. Geological Survey Professional Paper 813-E.
GB1025.C2T47 557.3'08s[333.9'104'09794] 75-619437

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02769-1

CONTENTS

ILLUSTRATIONS

TABLES

METRIC-ENGLISH EQUIVALENTS

Metric unit			English equivalent
Length			
millimetre (mm)	=	0.03937	inch (in)
metre (m)	=	3.28	feet (ft)
kilometre (km)	=	.62	mile (mi)
Area			
square metre (m^2)	=	10.76	square feet (ft^2)
square kilometre (km^2)	=	.386	square mile (mi^2)
hectare (ha)	=	2.47	acres
Volume			
cubic centimetre (cm^3)	=	0.061	cubic inch (in^3)
litre (l)	=	61.03	cubic inches
cubic metre (m^3)	=	35.31	cubic feet (ft^3)
cubic metre	=	.00081	acre-foot (acre-ft)
cubic hectometre (hm^3)	=	810.7	acre-feet
litre	=	2.113	pints (pt)
litre	=	1.06	quarts (qt)
litre	=	.26	gallon (gal)
cubic metre	=	.00026	million gallons (Mgal or 10^6 gal)
cubic metre	=	6.290	barrels (bbl) (1 bbl=42 gal)
Weight			
gram (g)	=	0.035	ounce, avoirdupois (oz avdp)
gram	=	.0022	pound, avoirdupois (lb avdp)
tonne (t)	=	1.1	tons, short (2,000 lb)
tonne	=	.98	ton, long (2,240 lb)
Specific combinations			
kilogram per square centimetre (kg/cm^2)	=	0.96	atmosphere (atm)
kilogram per square centimetre	=	.98	bar (0.9869 atm)
cubic metre per second (m^3/s)	=	35.3	cubic feet per second (ft^3/s)

Metric unit			English equivalent
Specific combinations—Continued			
litre per second (l/s)	=	.0353	cubic foot per second
cubic metre per second per square kilometre [$(m^3/s)/km^2$]	=	91.47	cubic feet per second per square mile [$(ft^3/s)/mi^2$]
metre per day (m/d)	=	3.28	feet per day (hydraulic conductivity) (ft/d)
metre per kilometre (m/km)	=	5.28	feet per mile (ft/mi)
kilometre per hour (km/h)	=	.9113	foot per second (ft/s)
metre per second (m/s)	=	3.28	feet per second
metre squared per day (m^2/d)	=	10.764	feet squared per day (ft^2/d) (transmissivity)
cubic metre per second (m^3/s)	=	22.826	million gallons per day (Mgal/d)
cubic metre per minute (m^3/min)	=	264.2	gallons per minute (gal/min)
litre per second (l/s)	=	15.85	gallons per minute
litre per second per metre [(l/s)/m]	=	4.83	gallons per minute per foot [(gal/min)/ft]
kilometre per hour (km/h)	=	.62	mile per hour (mi/h)
metre per second (m/s)	=	2.237	miles per hour
gram per cubic centimetre (g/cm^3)	=	62.43	pounds per cubic foot (lb/ft^3)
gram per square centimetre (g/cm^2)	=	2.048	pounds per square foot (lb/ft^2)
gram per square centimetre	=	.0142	pound per square inch (lb/in^2)
Temperature			
degree Celsius (°C)	=	1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	=	[(1.8×°C)+32]	degrees Fahrenheit

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES—CALIFORNIA REGION

By H. E. Thomas and D. A. Phoenix

ABSTRACT

Most people in the California Region live in a semiarid or arid climate, with precipitation less than the potential evapotranspiration—environments of perennial water deficiency. The deficiency becomes most onerous during the characteristically rainless summers and during recurrent droughts that may continue for 10–20 years. However, water from winter rain and snow can be stored for use during the dry summer months, and water stored during a wet climatic period can be used in a succeeding dry period; moreover, perennial deficiency can be overcome by bringing water from areas of perennial surplus. Ground-water reservoirs have especial significance in arid and semiarid regions as repositories where water is stored or can be stored with minimum loss by evaporation.

Nearly all the ground-water reservoirs of the California Region are in alluvial sediments of valleys and plains that flank the mountain ranges. The largest, underlying the vast Central Valley, occupies 10 percent of the area of the region, has an estimated usable capacity exceeding 100 million acre-feet (125 cubic kilometres), and has an annual pumpage from wells of about 13 million acre-feet (16 cubic kilometres). Another 10 percent of the region is occupied by 55 developed ground-water reservoirs that are widely distributed; aggregate annual pumpage from them is about 3½ million acre-feet (4 cubic kilometres). In the southeastern desert about 60 ground-water reservoirs occupy still another 10 percent of the region; these have been explored only enough to show that most have some usable water, but current use is negligible. In northeastern California and adjacent Oregon and Nevada, ground-water reservoirs are identified only in valleys and lowlands where wells are feasible, but basaltic rocks of the Cascade Range and Modoc Plateau are excellent aquifers distributed over an area constituting about 15 percent of the region. In sum, slightly less than half the California Region is underlain by ground-water reservoirs, either in valley fill or in volcanic rocks, which can yield significant quantities of water to wells.

The rest of the California Region includes the mountains, canyons, slopes, and foothills of the Sierra Nevada, Coast Ranges, and Basin Ranges, whose consolidated rocks and products of their weathering may be permeable locally but are not generally so. Here, the prevailing method of ground-water development is still mostly trial and error, and while in many places a well can yield enough water for a family, some families might have to do without amenities such as flush toilets and automatic washers.

For more than half a century the California Region has led all others in North America in pumping of ground water as well as in the area, variety, yield, and export of crops irrigated by water from wells. It has led in the development and use of deep-well turbine pumps for large yield and in the drilling of water wells to great depths. At the same time, such developments have resulted in the elimination of artesian pressures that produced thousands of flowing wells in the 19th century and led to the wide distribution of "falling water tables." Also, California was first to induce encroachment of seawater into wells (in 1906); first to recognize subsidence of land caused by pumping from wells (in 1933), generating news about land sinking in San Jose, Long Beach, and along the Delta-Mendota and Friant-Kern Canals; and first to experience pollution of ground-water reservoirs by brines, chemicals, industrial wastes, and petroleum byproducts including gasoline. The region has led in research in several fields leading to solution of many of these problems.

Ground-water problems developed rapidly after World War II with booming population, agriculture, industry, and water demand during several years of regionwide drought. Water levels in wells trended downward almost everywhere as a natural effect of the drought and at accelerated rates in areas of pumping for new enterprises or to supplement subnormal surface-water supplies. The declines in many pumping areas exceeded 100 feet (30 metres), and in some confined aquifers the potentiometric surface was drawn down more than 330 feet (100 metres). The depletion of ground-water storage has had "permanent" side effects, including subsidence of the land exceeding 10 feet (3 metres) in extensive areas, and seawater intrusion that ended the useful lives of many wells along the coast and as much as 6 miles (10 kilometres) inland. Some problems have been solved, but these solutions have at times created other problems. Many ground-water reservoirs have gone through one or more stages—exploration for productive aquifers, exploitation and development for use of the water, restriction to the perennial supply or "safe" yield, importation of surface water, artificial recharge of ground water, conjunctive use of surface and ground water, protection of water quality, and integrated management of use and disposal of water. This evolutionary sequence is unique for each reservoir, and so generalizations become difficult in a regional appraisal; also, the changes with time are significant and varied, and knowledge of prior events is a prerequisite in an appraisal of the resource in a specific year.

As of 1970, water levels in many wells had risen significantly from the minimum levels of record reached during the 1960's or earlier; only in areas of new development and in desert areas of long-continued "mining" of nonreplenished water was ground-water storage still being depleted. Land subsidence has continued at diminishing rates and practically has come to a halt in some areas; invading seawater has been stopped or nudged back in most places where problems were significant. The current, favorable situation has been helped by climatic variations, from drought in 1945-52 and exceedingly dry years in 1959 and 1961 to above-normal precipitation in 1969 and 1970; but most of the serious problems have been solved by human efforts, including especially the implementation of the California Water Plan, transporting water from areas of perennial surplus to areas where it is used in lieu of ground water or for ground-water replenishment. All major urban areas now import water to supplement or replace the water pumped from wells. Extensive agricultural areas that formerly were irrigated solely by ground water now obtain some of their water from surface reservoirs and canals, especially in the Central Valley. With surface water available as an alternative supply, well owners can view their ground

water with complacency. But complacency can lead to neglect and carelessness and consequent deterioration of the ground-water resource by pollution.

Claiming heritage from the English Common Law, the existing California law grants to the landowner (riparian) and private enterprise (appropriator) rights to the water stored in ground-water reservoirs or discharged from them, including the base flow of streams. Ground-water development has been by private and local enterprise, and the California legislature has protected and encouraged local responsibility, control, and management of ground water. As to surface water, a constitutional amendment in 1928 limited riparian rights to the quantities of water that were "reasonably required for the beneficial use to be served." The surpluses have become public waters which are collected, stored, transported, and delivered under various contracts by Federal, State, and other agencies. The agencies have not stored water underground because of uncertainty as to their rights, but some local agencies have been encouraged with favorable pricing schedules to undertake the artificial recharge and management of ground-water reservoirs. Thus, conjunctive use of surface and ground water has become a matter of interagency negotiation.

Of all the constraints on effective use of ground-water reservoirs, the most formidable may be the attitudes of people. Assurance of water supply is vital in areas of water deficiency, and Government has assumed increasing responsibility for the welfare of people in these areas. Unfortunately, when Government provides this assurance, most beneficiaries demand continued subsidy to the exclusion of perhaps cheaper private development. Indeed, as the water resources are presently segregated—with private rights predominant in ground water and public interest dominant in surface water—ground-water development has suffered for lack of public concern. The region has the scientific and technologic capability for effective use of ground-water reservoirs, as shown by the achievements and programs of several districts, but many districts are not organized or staffed for such comprehensive management and will need assistance and scientific expertise available from State and Federal agencies. Those agencies, in turn, may not have the scientific data that are essential to prevent haphazard activities and to enable programs to be organized for the most effective and attractive utilization of the water resources. In these days of increasing concern over pollution, existing data are generally inadequate to assess the natural deterioration of ground waters as a basis for defining pollution.

REGIONAL ENVIRONMENT

The California Region (fig. 1) comprises coastal valleys and the Coast Ranges, interior valleys and the Sierra Nevada, volcanic terranes and desert areas, fertile lands and wastelands, and the Pacific Ocean, which Tannehill (1947) called "the monster in the backyard" because of its great involvement in the climate and therefore the water resources of the region. By comparison with other water-resource regions of the country, the California Region is outstanding in the variety of its environments, ranging from very wet to very dry, very low to very high, surplus of sunshine to surplus of fog, prevailing high winds to prevailing calm. Despite this diversity, the entire region shares the characteristic that summers are dry. About 85 percent of the annual precipitation can be expected in the 6 months November to April. In most of the region, the rainfall in the 4 hottest months (June-September) is less than 5 percent of the annual total.

To meet the continuing requirements of life, some water from the rainy season must be available throughout the dry summer (fig. 2). Native vegetation is able to subsist on water collected by deep perennial root systems; annuals must ripen their seeds after making their vegetative growth in spring before the soil water available to their roots is exhausted. Animals have the advantage of mobility to search out the places where suitable water is available in the dry season. For mankind, seasonal aridity has provided various perils of occupancy, epitomized by the name Death Valley—the region's lowest, hottest, and driest valley.

PERILS OF OCCUPANCY

In the northern part of the California Region and in the high Sierra Nevada, the mean annual precipitation of more than 40 inches (1,000 mm) exceeds the annual evapotranspiration, and the perennial water surplus eventually becomes runoff in streams. But perennial water deficiency characterizes all of southern California and practically all the lowlands farther north—lands where the majority of the people in the region live. This water deficiency is a natural condition of the climate that is related to but distinct from water demands or water requirements of man and his crops and other activities. As pointed out by Thornthwaite (1948, p. 56); "The vegetation of the desert is sparse and uses little water because water is deficient***. When water supply increases, as in a desert irrigation project, evapotranspiration rises to maximum that depends only on the climate. This we may call 'potential evapotranspiration,' as distinct from actual evapotranspiration."

By Thornthwaite's empirical formula, potential evapotranspiration can be estimated for any locality if the mean monthly temperature and the latitude are known. In the San Joaquin Valley and the desert east of the southern Sierra Nevada and southern Coast Ranges, the deficiency ranges from 20 to 40 inches (500 to 1,000 mm) annually, equivalent to 1–2 Mgal/d/mi^2 (million U.S. gallons per day per square mile) (1,460 to 2,920 m^3 per day per km^2) (Piper, 1965); the deficiency is greater along the southeast border of the region (fig. 3). Studies (Cruff and Thompson, 1967) indicate that the Thornthwaite formula gives consistently low estimates of potential evapotranspiration in dry regions; thus actual water deficiencies may be greater than those indicated in figure 3.

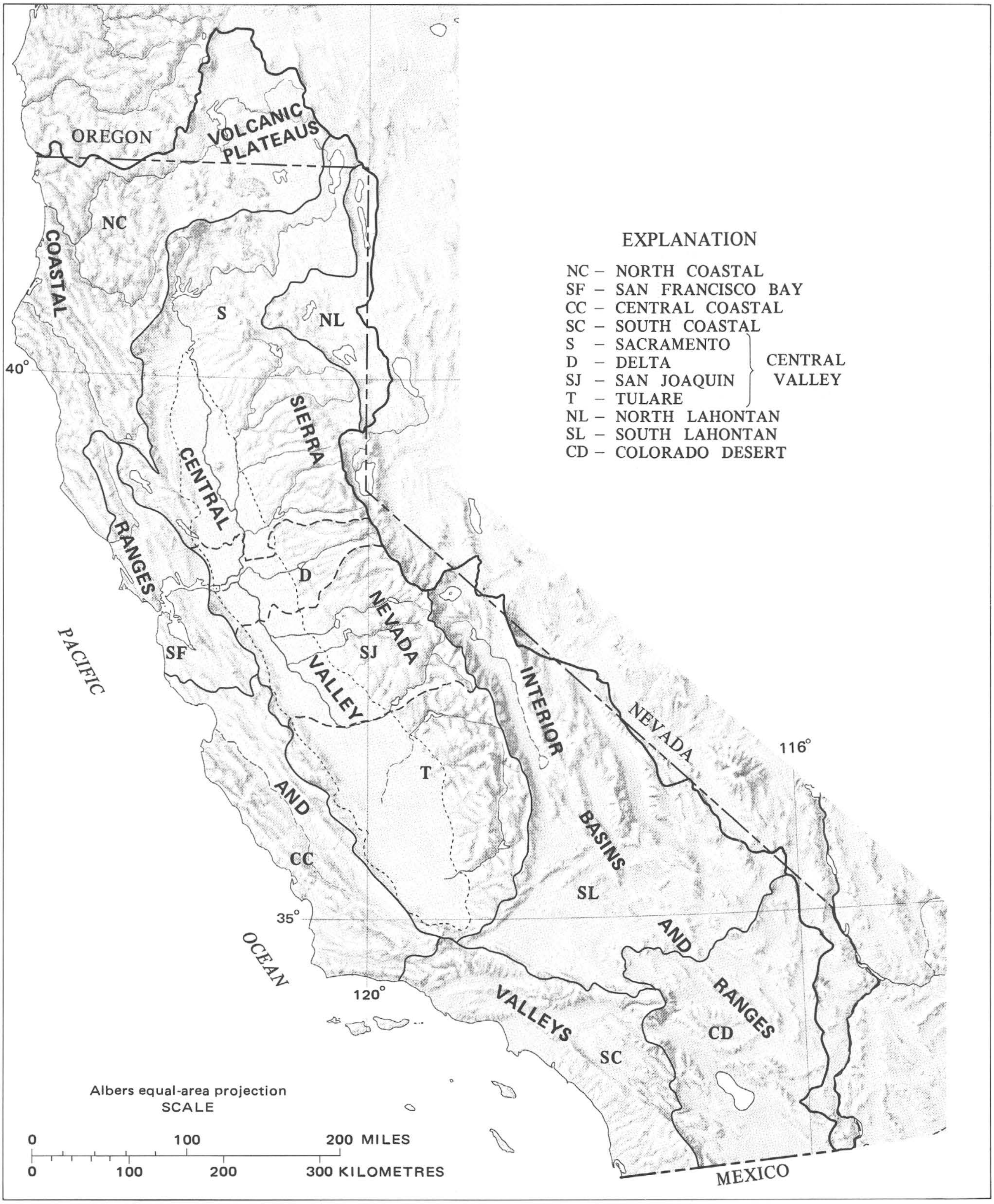


FIGURE 1.—Subregions and landforms of California Region

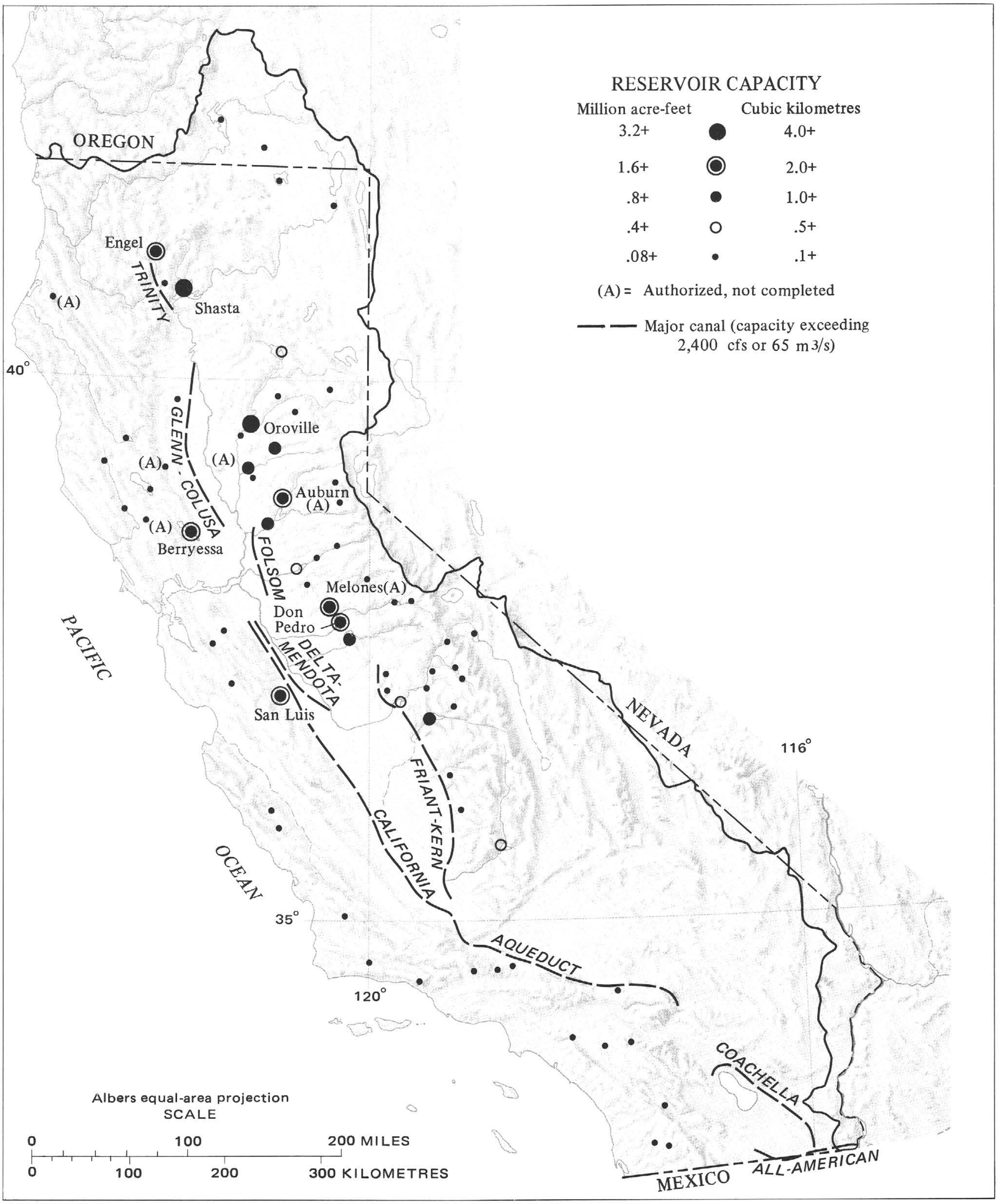


FIGURE 2.—Major surface reservoirs and canals in the California Region.

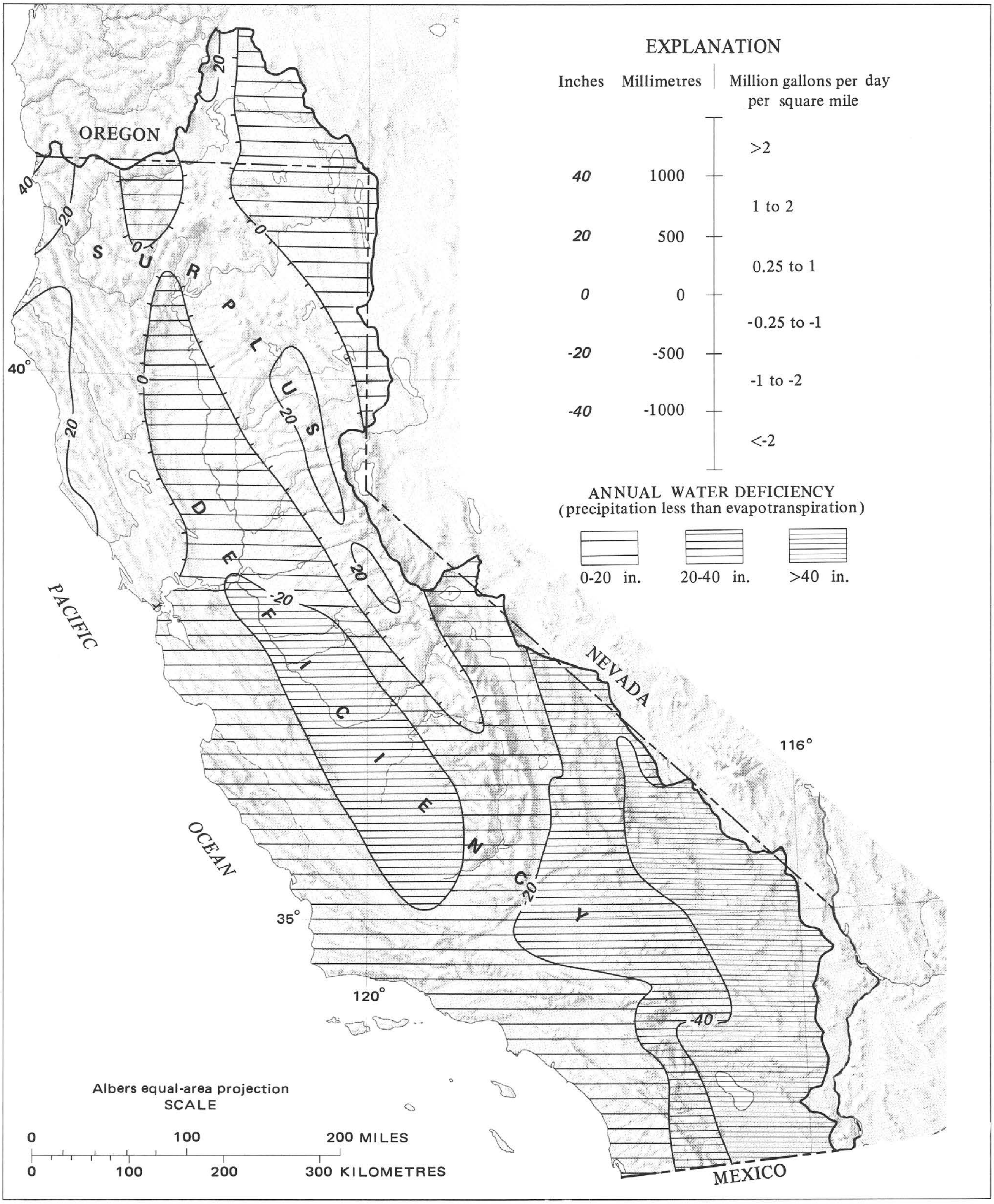


FIGURE 3.—Water surplus and water deficiency in the California Region

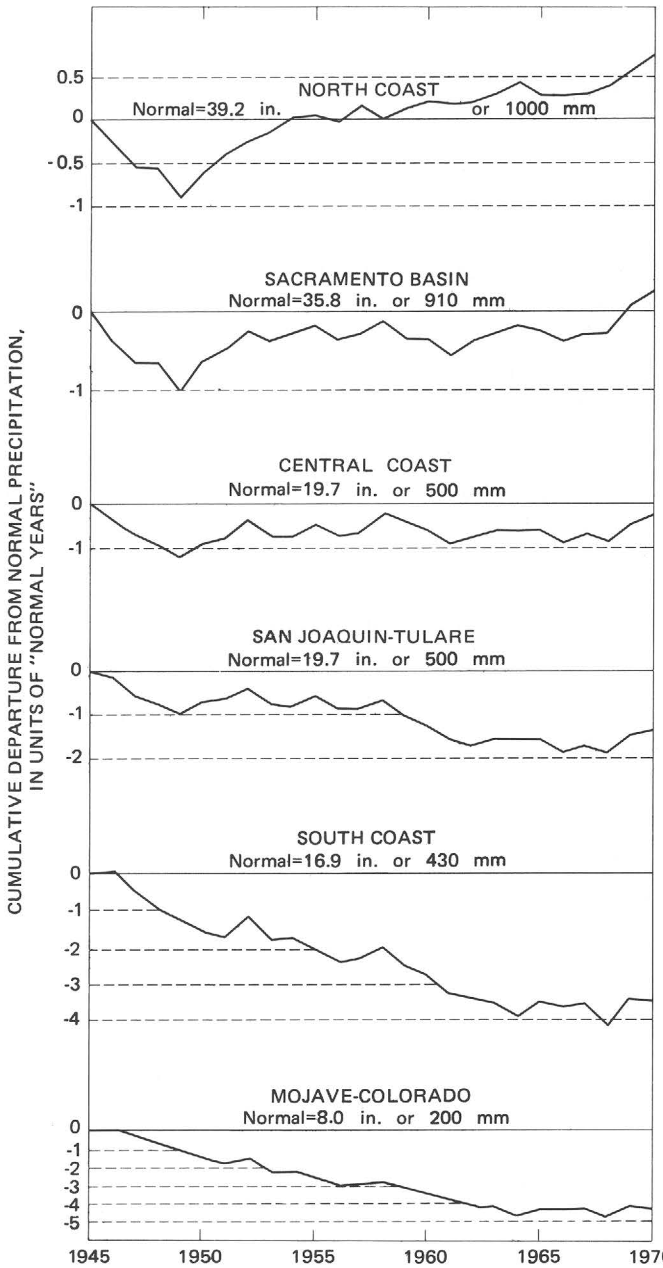


FIGURE 4.—Precipitation trends by subregions, 1945–70.

According to climatologic data the greatest water deficiency in the region is in Death Valley, where the average annual rainfall is 1.6 inches (40 mm) but evaporation from a standard land pan is more than 140 inches (3,500 mm). Annual evaporation from lakes and reservoirs in the California Region (Kohler and others, 1959) ranges from less than 28 inches (730 mm) along the north coast to more than 86 inches (2,200 mm) in the southeastern deserts including Death Valley. In the valleys of southern California where mean annual precipitation is less than 16 inches (400 mm) the June-September rainfall is negligible, and summers are dry and hot. In the northern part of the region, the summer rainfall is greater but still is less than 5 percent of the annual total; the summers are relatively cool, and many forms of life subsist on water from the preceding wet months, supplemented by occasional rain and fog.

The average annual precipitation and evapotranspiration and the mean seasonal characteristics of precipitation are based on records for the 30-year "normal" period 1931-60. But in every locality the precipitation varies markedly from year to year. At San Diego the normal precipitation is 10.4 inches (265 mm), but during a century of record its precipitation has ranged from 27.6 inches (700 mm) in 1884 to 3.4 inches (85 mm) in 1953. In the desert, the maximum annual rainfall at Indio (in 1939) was 35 times the minimum in 1923. It is the deviations from average precipitation, particularly the variations that cause outstanding floods and droughts, that are perilous and sometimes disastrous in the region.

The "normal" period (1931-60) includes 5 years of the 1924–35 drought, which was more severe in the northern part of the region than in the southern part. During the next 10 years, however, precipitation was above normal in all parts of the region, and the records included 2 years of highs unsurpassed in the 20th century to date, 1938, the wettest year, and 1941, the year of greatest runoff, including disastrous floods in the normally deficient Los Angeles area. In the years 1945-49 (fig. 4), precipitation was only about 75 percent of normal, and all parts of the region had a deficiency equivalent to one year's precipitation. Since 1950, above-average precipitation in the north has made up for that "lost" year, but continued less-than-normal precipitation in the San Joaquin Valley produced an accumulated deficiency of about 2 years of average rainfall by 1968. In southern California, precipitation was also prevailingly less than average, and the accumulated deficiency as of 1970 was equivalent to nearly 4 years of average rainfall. Official records indicate that comparable dry periods have occurred in Los Angeles and San Diego in 1917–34, 1894–1904, and 1870–83 and, according to diaries of missionaries, 1843–59, 1822–32, and 1793–1809, with intervening wetter periods (Thomas, 1962). Although the entire region is subject to relatively long periods during which precipitation and runoff have been materially above or below the long-term mean, southern California is subject to more severe and longer variations than is the northern part of the region.

AIDS TO SURVIVAL

The mountain-and-valley topography greatly influences the distribution of precipitation over the region and has also influenced the distribution of human population, which is concentrated in precipitation-deficient valleys. These flat lowlands and valleys so highly prized for agriculture, commerce, industry, and urban dwelling have always relied on the neighboring mountains for runoff as surface water or ground water which can supplement the scant rainfall of the valleys.

In the Coast Ranges and low desert mountains, streamflow is predominantly storm runoff produced by and almost concurrent with intense or lengthy rainstorms; in the desert most stream channels carry water only after exceptional rainstorms. The streamflow in the Coast Ranges is closely related to rainfall and more than 95 percent of the annual total occurs during the 8 rainy months. Runoff during the rainy season can be stored for use during the dry season, and such storage occurs naturally in areas such as snowfields and lakes.

Snow may accumulate in areas of the Coast Ranges and Sierra Nevada above an altitude of 4,000 feet (1,200 m); above 6,000 feet (1,800 m) the seasonal snowfall commonly exceeds 78 inches (2 m). The snow in the Sierra generally accumulates until April, and its melting produces an annual freshet that reaches a peak in May; 20–40 percent of the annual runoff of streams draining the High Sierra occurs in the 4 summer months. The snow disappears during the summer, and by September and October these streams reach their minimum flow of the year.

The numerous natural lakes of the California Region are mostly in high mountains that have a perennial water surplus. They store water during the period of greatest inflow and release it gradually to sustain the runoff, perhaps throughout the year. Many of these lakes are now dammed to increase the storage, and many manmade lakes have been created by dams in areas of perennial surplus to store water during the periods of greatest inflow and release it as desired, particularly to meet demands during the dry season.

Many natural and manmade lakes are, however, in areas of perennial water deficiency, an environment in which evaporation may be equal to the inflow, and so there is no outflow; or outflow may exceed the inflow until the lake dries up. For example, Goose Lake in the northeastern part of the region had an area of about 185 square miles (480 km^2) and overflowed to the Pit River in 1869 and again in 1881, but the lake has had no outflow for many years, and during a drought beginning in 1924, the lake dwindled until it dried up in 1930. In the southeast desert most of the closed basins have a "dry lake" in their lowest part, where water accumulates by inflow from exceptional storms and then is dissipated by evaporation. Other lakes have sufficient inflow to be perennial, but as water is evaporated the dissolved salts remain behind and the water in the lake becomes increasingly saline.

Many large artificial lakes and reservoirs have been created in areas of water deficiency to store water in times of surplus for use in places of need. This storage of water for man's use is usually expensive, and as with natural lakes, evaporation from the lake surface reduces both the quantity and the quality of the water stored. Although the cost of surface storage has long been accepted by the State of California, it was cited by Conkling (1946, p. 279) as a basis for recommending alternative use of subsurface storage wherever feasible:

> A study of evaporation losses from hypothetical surface reservoirs on all streams in California indicates that, no matter how large the reservoir capacity, streams of erratic annual and cyclic flow will yield for useful purposes no more than 50 percent or 60 percent of the annual average discharge because the remainder will be lost, over the years, by evaporation from the excessive water surface of the reservoir necessary to impound the water of the infrequent years of large discharge.

SIGNIFICANCE OF GROUND-WATER RESERVOIRS

Ground-water reservoirs have always been significant because of their capability of storing usable water, perennially secure from loss, but especially so during the rainless summers and in the perennially water-deficient areas of the California Region. Because surface water in streams, lakes, marshes, and snowfields and soil moisture are vulnerable to evapotranspiration and progressive depletion between storms, ground water is the most reliable source of potable water in many parts of the region and in fact is the only source in some areas.

Natural sources of ground-water discharge are springs, seepage areas, lakes, and base flow of perennial streams, used by Indians, missions, and early settlers. As population increased during the 19th century, more ground water was located by digging wells, tunneling in sloping lands, and boring artesian wells, chiefly for domestic use. Large-scale development and use of ground water became possible in the 20th century, with advancing technology in well drilling and motor-driven pumps. In 1950, irrigation wells pumped 10 million acre-feet (12 km^3) equivalent to the volume of surface water used within the region and almost as much ground water as was used for irrigation in all the rest of the United States.

A century of development proved that ground water is distributed widely, though not uniformly, in the region, especially under the valley floors where it is withdrawn by thousands of large and productive wells and also in many foothill and mountain areas where wells and springs yield water sufficient for domestic use. The storage of potable water in ground-water reservoirs is many times as great as the capacity of all natural lakes plus artificial reservoirs, existing and contemplated. From early days ground-water development has also created problems in many areas—"falling water tables," overdraft and progressive depletion of storage, seawater encroachment and deterioration of quality in freshwater aquifers, and compaction of water-bearing sediments and subsidence of the overlying land.

As development and use of ground water increased, people in many water-deficient areas became concerned about inadequacy or impermanence of their ground-water supply and about obtaining water from other sources, and thus a State Water Plan was proposed in a report to the 1931 legislature (California Department of Water Resources, 1930). The later and present California Water Plan was far more comprehensive and pointed out (California Department of Water Resources, 1957a, p. 242) the necessity for "the development and use of vast regulatory and carry over storage capacity, both surface and underground, in order to attain the degree of conservation required to meet water needs under ultimate conditions of development; and the construction and operation of a major system of works to convey the regulated excess waters from areas of inherent surplus to areas of inherent deficiency."

The implementation of the California Water Plan to date has been concerned chiefly with facilities for storage and transport of surface water from places of surplus in order to satisfy water demands in various areas in the immediate future. The region in 1970 had 11 surface reservoirs of capacity greater than 800,000 acre-feet (1 km^3); their combined usable capacity was about 23 million acre-feet (28 km^3) slightly less than that of Lake Mead on the Colorado River. There are 60 smaller reservoirs with capacity greater than 80,000 acre-feet (100 million m^3), and these increase the surface-water storage in the region to more than 40 million acre-feet (50 km^3) (fig. 2), equivalent to 55 percent of the average annual runoff. Many of the reservoirs in the California Region were created before environmental awareness became fashionable; thanks to good planning, good fortune, and public acceptance, these reservoirs have caused far less environmental disruption than has been reported as a result of superdams on other continents, and many are significant enhancements. Figure 2 shows the major components of the Central Valley Project and State Water Project, including several that were authorized but not yet under construction in 1970.

There is increasing recognition that ground-water reservoirs are significant not only for the water they contain but also for the space in which water may be stored for years with minimum loss. This is expressed in a recent summary of planning within the California Water Plan (California Department of Water Resources, 1970c, p. 72):

> Ground water in storage and ground water storage capacity constitute an extremely valuable resource at present and will continue to be in the future. The value of ground-water resources lies in the use of ground water in storage and under-ground storage capacity (1) to provide regulation of natural replenishment, and (2) operated coordinatedly with both local and imported surface supplies, to effect the most economical use of total available storage, both surface and underground, as an integrated system.

GROUND-WATER RESERVOIRS

The term "reservoir," from the French, has been used especially for artificial lakes and some natural lakes. Implicit in this usage is the delaying and storing—reserving—of surface water in its flow through the hydrologic cycle. If one of these lakes were filled with gravel or sand, its water storage would be reduced by two-thirds, and the rate of movement of water from points of inflow to outflow would be reduced; it would then have the characteristics of a ground-water reservoir. Ground-water reservoirs exist in nature, but their extent, depth, capacity, and the variations of the quality of the water in them are known only as knowledge is acquired in the course of prospecting for, developing, and withdrawing water from them. Most ground-water reservoirs contain far more water in storage than the volume that flows through them annually; however, only this flow-through volume is the renewable resource, the sub-surface phase of the hydrologic cycle.

As used in this appraisal, a ground-water reservoir may contain several water-bearing zones, or aquifers, at various depths and having varied thickness and areal extent. Aquifer is more specifically a geologic term, referring to a rock formation or group, or part of a formation, that is water bearing. Basin, a term in common use for surface-water drainage, may also be applied to a geographic area containing a well-defined ground-water reservoir or part thereof.

NATURAL HISTORY

Most of the ground-water reservoirs of the California region are in the valleys and plains that receive runoff and debris from the mountains. The longest and highest mountain range is the Sierra Nevada, a broad tilted block of relatively impermeable igneous and metamorphic rocks extending from the south end of the Cascade Range at Mt. Lassen southward 400 miles (640 km). To the west, the great Central Valley of similar length and breadth is composed partly of stream-borne sediments that now contain freshwater to depths of 400 to more than 4,000 feet (120 to 1,200 m) below sea level.

The Central Valley ground-water reservoir includes numerous gravel-and-sand aquifers, formed by stream-carried sediments from the mountains, separated by interstream sediments of chiefly silt and clay; it also includes deep confined aquifers which are separated from shallow aquifers by extensive beds of clay. Also, the pattern of precipitation and surface inflow—generally greater in the north, less to the south—is responsible for other variations in ground-water occurrence. This ground-water reservoir is thus a complex and heterogeneous mass, too large to consider conveniently as a unit and yet with sufficient unity that division on the basis of ground-water characteristics is difficult. For overall water-resource studies and planning in the California Region, the Central Valley drainage basin is divisable into at least two subregions—the Sacramento basin to the north and the San Joaquin Basin southeast of the valley's outlet to San Francisco Bay; it has been divided additionally to form the Delta, where the valley floor is approximately at sea level, and the Tulare Basin of interior drainage at the south end of the Central Valley (fig. 1).

The Coast Ranges comprise folded and faulted sedimentary and metamorphic rocks generally parallel to the Pacific coastline. Most of the ground-water reservoirs are in the intervening structural valleys and coastal plains; some are along the streams that drain, traverse, or bypass various ranges as they flow toward the ocean. The coastal valleys and mountains are included in four subregions—North Coastal, San Francisco Bay, Central Coastal, and South Coastal—of the California Region, each comprising drainage basins of several streams debouching into the Pacific Ocean. The North Coastal subregion has the greatest precipitation and runoff; its ground-water reservoirs are recharged each rainy season and maintain perennial flow of streams in the rainless season. Water deficiency is prevalent in the South Coastal subregion, where ground-water reservoirs are recharged in wet seasons but where the water may remain underground as it moves toward the ocean, appearing at the surface only where it encounters faults or other barriers.

East of the Sierra Nevada and the Transverse Ranges farther south, the California Region includes the Mojave Desert, the Colorado Desert, and the valleys and ranges of the Great Basin in California, designated the North and South Lahontan subregions. Separated from the Pacific Ocean by formidable mountain barriers, these areas are the most arid lands of the region, all in basins of interior drainage except for a narrow zone along the through-flowing Colorado River. The Mojave, Owens, and Susan Rivers are the largest of the few streams with headwaters in high mountains that yield perennial inflow to these arid basins. Other stream channels are dry except when rare torrential storms cause floods of short duration or during brief snowmelt seasons. Ground-water reservoirs are found under the valleys and plains and may be recharged chiefly by intense storms or flood runoff. Discharge from these ground-water reservoirs may be by springs, by evapotranspiration where water is at shallow depth, or by subsurface movement toward a lower valley. For example, some water in the Mojave River may recharge ground water and continue downgradient as subsurface flow through half a dozen valleys, perhaps eventually contributing to the "Badwater" of Death Valley.

In the northeastern part of the California Region, the Modoc Plateau consists of a thick accumulation of lava flows and tuffs and small volcanic cones. Many of these volcanic rocks are excellent aquifers, readily recharged by precipitation and permeable enough to store and subsequently discharge water at numerous large springs, although most of the plateau is in the rain shadow of the Sierra-Cascades and is semiarid. The total area of these volcanic rocks exceeds 10,000 square miles (26,000 km^2), which is chiefly highlands and slopes undesirable for drilling wells or using the water from them. The ground-water reservoirs outlined in this volcanic area (pl. 1) include only the plains or valleys where ground-water development is active or likely. Some of these valleys are in the Klamath River basin (North Coastal subregion), and others are in the Sacramento River basin and subregion or in the North Lahontan subregion, part of the Great Basin.

HISTORY OF DEVELOPMENT AND USE

The original and aboriginal inhabitants of the California Region adapted well to their environment, hunting, fishing, and taking food and water where they found them. In rainless summers and in deserts, the Indians necessarily depended upon ground water that came to the surface as the base flow of streams or that was found in springs, waterholes, or plants.

The arrival of the Spaniards in 1769 saw the introduction of traditions and practices that had been developed in arid and semiarid regions where the value of land depended upon the availability of ground or surface water. The first dams, reservoirs, aqueducts, and wells in the region were constructed at the California missions, and gardens, vineyards, orchards, and field crops were planted and irrigated. Development and use of ground water at the missions was minor: Cienegas discharged a copious supply for the San Gabriel and San Fernando Missions, wells were dug at several other missions when stream supplies became inadequate, and at the San Antonio Mission a noria (undershot water wheel) was constructed to lift water from a dug well for irrigation of a garden and vineyard.

The independence of Mexico in 1824 and the secularization of the missions in the following decade marked the beginning of the era of the Californios, Spanish families who had obtained about 30 grants of land from the Spanish government prior to 1822 and nearly 800 grants from the Mexicans by 1846 (Pitt, 1966). The maximum grant to an individual was 11 square leagues (about 99 square miles or 250 km^2), including 1 of irrigable land, 4 for dry farming, and 6 for grazing. By 1849 an estimated 200 families of Californios had been granted 14 million acres (56,700 km^2) of prime land, especially in the South Coastal, Central Coastal, and San Francisco Bay subregions.

The Mexican War, which ended with the cession of California to the United States in February 1848, brought new settlers to the California Region with a contrasting culture of Anglo-Saxon traditions and customs. Their esteem for the yeoman who could wrest a decent livelihood by rainfall agriculture on 160 acres and their equal distaste for those who left resources idle or failed to make the most of them prompted many of these newcomers to move onto the rancho lands and assert squatter's rights on the basis of their occupancy. Many obtained title to land through legislation, litigation, purchase, or financial or legal manipulation; however, most of the grants to Californios were eventually accepted. Titles were confirmed by Federal courts for about 600 of the grants with a total area about 9 million acres (36,400 km^2), and a few have remained virtually intact to the present.

The influx of settlers was accelerated tremendously after the discovery of gold in the Sierra Nevada in January 1848. In the gold country men staked their claims, built their camps, and appropriated water and wood and brought them to their workings for their operations, all as trespassers on the public land. The miners acted like the squatters on agricultural lands, but subsequent generations recognize that they applied the doctrine of prior application—first in time is first in right—to the water and to the mining claims. This law of water subsequently became the water law in most other States of the arid West.

In 1850, before California became a State, the Legislature enacted a statute declaring the common law of England "the rule of decision in all the courts of the State." This was a triumph of English over Spanish culture, and it also imposed upon an arid and semiarid region the traditions of a well-settled and orderly humid region. The common law had little to say about squatter's rights or appropriative rights but had strong support for landownership. It included the doctrine that each owner of land bordering a stream had a right to the natural flow of the stream, undiminished in quantity and unimpaired in quality, and that each riparian owner, but no nonriparian owner, had the right to use the water and this right was not lost by nonuse. Conflicts soon arose between riparians and appropriators of water. The riparian rights to natural flow could restrict or prevent the storage of winter runoff from rain or of spring runoff from melting snow to be used for irrigation when natural streamflow was negligible. Consequently, construction of large dams on California streams came slowly, years later than the first large dams in any other western State. It took a constitutional amendment (article XIV, sec. 3) in 1928 to limit riparian rights to the quantities of water that were "reasonably required for the beneficial use to be served."

The common law also included the English rule that a landowner owns the percolating water beneath his land and can do as he pleases with it.[1] Thus to nonriparian landowners, and to riparians who could not store water to use when they needed it most, ground water would be a lifesaver if it could be obtained in quantities sufficient for irrigation, the predominant use.

During the 19th century the most productive wells were flowing artesian wells: only a few in the 1860's but increasing to thousands in the next decade so that the Legislature in 1878 enacted a statute to prevent waste from flowing wells. In 1890 about 3,200 flowing wells irrigated 4 percent of the 1 million irrigated acres (4,000 km^2) in the region. In 1894 a well was pumped by electric motor, and by 1906 some 600 pumped wells in San Joaquin Valley had a combined yield of 7,660 ft^3/sec (cubic feet per second) (220m^3/s), more than five times the yield of the 520 flowing irrigation wells.

In the course of this water development, wells started interfering, artesian pressures declined, and litigation ensued, during which it became evident that the common-law doctrine of absolute ownership of ground water was unsuited to California conditions.[2] A leading decision by the California Supreme Court (Katz v. Walkinshaw, 1903) resulted in the California doctrine that the owners of land overlying a ground-water reservoir have correlative rights in a common supply and that each owner is limited to reasonable beneficial use of the water. If a ground-water reservoir cannot yield perennially enough water to irrigate the overlying

[1]In contrast to this doctrine that percolating water belongs to the overlying landowner, the States of Nevada and Oregon have declared that all waters within their boundaries belong to the public and are subject to appropriation for beneficial use as provided by statute. Because of the contrasting doctrines of ground-water rights in the several States, the Water Resources Council has drawn the boundaries of the "California Region" to include all closed basins of the Great Basin that lie entirely within the State of California and also the interstate closed basins that drain California. Thus the boundary between the California Region and the Great Basin Region (pl. 1) is a hydrologic boundary that approximates the State boundary without dissecting ground-water reservoirs or stream drainage basins.

[2]This was a doctrine in the State of California, not the portions of the California Region that lie within Nevada and Oregon, which long ago repudiated the common-law doctrines of water rights.

land, this doctrine permits all owners to share in the deficiency. Furthermore, if an appropriator is pumping water from the reservoir for export, the landowner's right extends only to the water necessary for use on his land, and the appropriator may take any surplus.

In 1939 more than 50,000 wells were used to irrigate 1½ million acres (6,000 km^2) and to sustain another 1 million acres through the summer when stream supplies were minimal. By 1950 the total irrigated area in the region exceeded 6½ million acres (26,000 km^2); 45 percent was irrigated solely and 18 percent partly by water from 80,000 wells. This increasing use of water was accompanied by "falling water tables" in practically all areas of development and complicating problems in many places. Many of these problems have been solved by obtaining water from alternative sources, generally surface water, and reducing withdrawals of ground water. But restriction or regulation of pumping raised questions as to the respective water rights of appropriators and of overlying landowners including both users and nonusers of the water.

A California Supreme Court decision, Pasadena v. Alhambra(1949) added a new principle to the correlative doctrine. Pasadena and Alhambra are cities that pump water from the Raymond Basin, a 40-square-mile (100-km^2) area in the northwestern part of the San Gabriel Valley ground-water reservoir; Pasadena uses its supply within the basin, and Alhambra exports its supply. Both are classed as appropriators, for even though a city overlies a ground-water basin it does not own the land occupied by the people to whom it supplies water. In California, water may be appropriated for public use or for export so long as there is a surplus not used by overlying landowners, but evidence showed that beginning in 1913 there was no surplus; nevertheless, appropriators and overlying landowners continued to pump, the annual total averaging about 133 percent of the calculated "safe" yield of the basin. The decision was that pumpers who caused the overdraft acquired prescriptive rights by infringing upon superior overlying and appropriative rights for more than 5 years; however, the earlier users, continuing to pump to meet their needs, gained mutual prescriptive rights by infringing on the infringers. The "safe" yield was achieved by reducing proportionately the withdrawals of all users, and overlying owners who had taken no water lost their rights to water.

If the city fathers of Pasadena and Alhambra had known what was going on hydrologically, they might have called a meeting of all landowners of the Raymond Basin back in 1913 to announce that the surplus was just about gone, express appreciation for use of those surpluses all these years, and start looking for a new supply. Then it would have been up to the landowners with their correlative rights to work out ways to supply water to increasing numbers of people owning smaller and smaller plots of land, with all sharing the water deficiency; instead, the appropriators continued pumping for decades before going to court. The subsequent decision has become the prevailing law: An appropriative taking of water which is not surplus is wrongful but may ripen into a prescriptive right where the use is open and notorious, hostile and adverse to the original owner, continuous and uninterrupted for the statutory period of 5 years, and under claim of right. This principle has been the basis for adjudication of rights or for negotiation among right holders in several ground-water reservoirs in southern California and serves to specify the rights of each in the local resource.

Under the basic premise that ground water is part and parcel of the land, the development and use of ground water have been almost exclusively by private enterprise and local or community initiative. Particularly in early stages and in many places right down to the present, this development has been in response to the settlement, cultivation, and urbanization of the land, and thus haphazard and unplanned.

CHARACTERISTICS OF INDIVIDUAL RESERVOIRS

The characteristics of individual reservoirs are known chiefly from the wells and other excavations that have been dug, drilled, or tunneled into the earth. Some desert areas are devoid of inhabitants and wells, and geologic reconnaissances have provided the only information as to rocks and rock materials that may be water bearing; other areas presently uninhabited have been the sites of mining, agricultural, or other activities long ago, with or without record as to the sources of water supply. At the other extreme are ground-water reservoirs in which thousands of wells provide quantitative data as to aquifers and their boundaries, storage, and transmissivity. These best-known reservoirs have a history that may span several decades and perhaps a century, in which development has proceeded from exploration and exploitation to regulation and management. Moreover, each ground-water reservoir that has been identified and named in the California Region (California Department of Water Resources, 1952) can be classified on the basis of its current stage of development.

The uniqueness of individual ground-water reservoirs is the basis of recommendations that data-collection programs be organized on a basin-by-basin basis (Dutcher, 1972), and the California Legislature approves the established practice of keeping the development and management of ground-water reservoirs under local control. At times, however, the local agencies may need project reconnaissance studies

(Peters 1972b) to show the engineering and economic feasibility of a specific management program; these studies require very specific geologic and hydrologic information for the free ground-water zone and for each major confined zone to provide a hydrologic balance or model validation. For such tasks some agencies call upon expert consultants; others utilize the services of specialists in the California Department of Water Resources or the U.S. Geological Survey, under a cooperative or cost-sharing agreement.

EXPLORATION

If the total annual withdrawal is less than 8,100 acre-feet (10 million m^3 or 0.01 km^3), the ground water reservoir is here categorized as in the exploratory stage. Most reservoirs are included in the tabulation of undeveloped ground-water reservoirs in table 1, and all are shown on the regional map (pl.1). Some of these reservoirs are in uninhabited areas; most are in sparsely inhabited areas in which several wells have been dug or drilled chiefly for domestic or stock supplies. Some are tapped by a few large-capacity wells used for irrigation, military, industrial, or other purpose.

The 79 undeveloped ground-water reservoirs in the California Region range in size from 40 to 1,870 square miles (100 to 4,900 km^2), with an aggregate area of about 19,000 square miles (50,000 km^2). Data concerning these undeveloped reservoirs come chiefly from wells and may include well logs, measurements of water level or well discharge, and chemical analyses of sampled water. These data, plus any information from geologic maps and reports, are generally sufficient only for a precursory or cursory hydrologic study (Peters, 1972b). They are too meager to describe the areal extent, depth, and boundaries of aquifers or the storage, flow, or quality of the water in them in the detail necessary for sound development. In these reservoirs the natural equilibrium, inflow and outflow, is presumed to be unaffected by the negligible withdrawals from wells; the principal means of natural outflow from these reservoirs, known or presumed, is indicated in table 1.

EXPLOITATION

Exploitation of reservoirs is marked by successful development of large production wells, increasing numbers of wells, and increasing rates of pumping. The developed ground-water reservoirs of the California Region, including chiefly those having annual pumpage greater than 8,100 acre-feet (0.01 km^3), are given in table 2, with summary data on pumpage, estimated usable storage capacity, and water quality. Altogether 55 reservoirs are tabulated, underlying a total area of 30,000 square miles (77,000 km^2) of which half is in the Central Valley (table 3).

REGULATION

The fact or fear of overdevelopment, or the use of water at rates greater than the natural replenishment, generally results in restriction of pumping or additional development, in some instances voluntarily by agreement among water users or landowners, in other instances involuntarily by law. Under the doctrine of appropriation in most Western States, water belongs to the public and may be appropriated for beneficial use so long as there is surplus or "unappropriated" water; thereafter, the State may restrict or prevent additional development so that total withdrawals do not exceed the natural recharge.

In the State of California, regulation is unique both in timing and method. Ground-water development, by private enterprise, has not been subject to regulation until the need is established by clear evidence of overdraft, as presented during litigation calling for adjudication of ground-water rights. Because such adjudication requires a great volume and variety of quantitative data and study, the court may refer the case to the State Water Resources Control Board as referee (the court reference procedure) to be responsible for these studies. Effective regulation is likely to require reduction in pumping and denial of water to established users.

At the time of the leading decision placing restrictions on pumpage (Pasadena v. Alhambra, 1949), water imported from the Colorado River was available to those whose ground-water supplies must be reduced, and it is practically axiomatic that alternative sources of water shall be available as a supplement where it is necessary to reduce withdrawals from a ground-water reservoir to reach a "safe" yield. After rights are adjudicated, the extractions from the reservoir are monitored by a court-appointed watermaster who makes annual reports on water conditions, ground-water extractions and recharge, and imported water. Currently, watermaster service is provided for regulation of pumping in the West Coast Basin and Central Basin of the Los Angeles coastal plain (State Basin No. 4–11 on pl. 1), the upper Los Angeles River area of San Fernando Valley (No. 4–12), and the Raymond Basin of San Gabriel Valley (No. 4–13) (California Department of Water Resources, 1970d, e; 1971b, c).

MANAGEMENT

To achieve a "safe" yield from a ground-water reservoir or to make the best of limited natural resources, management may be imposed by public agencies or districts as authorized and encouraged by the State. These local water agencies are generally "users cooperatives" (Bain and others, 1966), most of which are

TABLE 1.—*Undeveloped ground-water reservoirs (withdrawals less than 8,100 acre-feet (10 million m^3) per year)*

[From Bader (1969) and California Region Framework Study Committee (1971), revised and updated]

State No.: Ground-water reservoir is numbered after California Division of Water Resources (1952) for California and by the Geological Survey for Oregon. Number before dash indicates California Regional Water Quality Control Board as follows: 1, North Coastal; 2, San Francisco; 3, Central Coastal; 4, Los Angeles; 5, Central Valley; 6, Lahontan; 7, Colorado River; 8, Santa Ana; 9, San Diego.
County: Where state name has asterisk (*), the ground-water reservoir is interstate, and the data given apply only to that part of the reservoirs within that state.
Natural outflow: ET, evapotranspiration; GW, ground-water outflow.

State No.	County	Ground-water reservoir	Estimated area (km²)	Natural outflow	Exploration data: Year	Number of wells	Depth explored (m)	Range in dissolved solids (mg/l)
		North Coastal subregion						
		Klamath River Basin:						
0–1	Klamath, Oreg.*	Klamath Marsh	600	Williamson River	1970	12	205	50–110
0–5	do	Langell Valley	180	Lost River	1970	10	150	130–170
0–6	do	Upper Klamath Valley	750	Klamath River	1954	13	145	80–100
0–7	do	Poe Valley	80	Lost River	1970	9	135	140–270
1–4	Siskiyou, Calif.*	Shasta Valley	650	Shasta River	1953	50	215	160–980
1–5	do	Scott River Valley	210	Scott River	1953	5	65	30–420
		San Francisco Bay subregion						
		Russian River basin:						
1–17	Sonoma, Calif.	Alexander Valley	100	Russian River	1954	40	135	220–1,300
		Central Coastal subregion						
		Closed basin:						
3–19	San Luis Obispo, Calif.	Carrizo Plain	700	ET-Soda Lake	1954	8	305	340–4,300
		Sacramento Basin subregion						
5–1	Lake, Oreg.*	Goose Lake Valley	410	ET-Goose Lake	1948	10	915	120–1,460
	Modoc, Calif.*	do	490	do	1964	15	230	100–450
		Pit River basin:						
5–2	Modoc, Calif.	Alturas basin	230	Pit River	1964	25	305	150–500
5–4	Modoc and Shasta, Calif.	Big Valley	260	do	1964	25	365	150–1,380
5–5	Shasta, Calif.	Fall River Valley	260	Fall River	1964	50	215	100–550
		Feather River basin:						
5–12	Plumas and Sierra, Calif	Sierra Valley	360	Feather River	1964	20	425	120–1,400
		San Joaquin Basin subregion						
5–23	San Benito, Calif.	Panoche Valley	130	Panoche Creek		--	120	--
5–25	Kern, Calif.	Kern River Valley	70	Kern River		(Partly overlain by Isabella Reservoir)		
		North Lahontan subregion						
		Closed basins:						
6–1	Modoc, Calif.*	Surprise Valley	910	ET-Alkali Lakes	1954	60	245	165–2,000
	Washoe, Nev.*	do	30					
6–2	Modoc, Calif.	Madeline Plains	700	ET-Tule Lake	1964	10	260	100–245
6–4	Lassen, Calif.*	Honey Lake Valley	1,270	ET-Honey Lake	1964	100	425	175–1,350
	Washoe, Nev.*	do	490	do	1967	10	120	170–5,000
		South Lahontan subregion						
		Closed basins:						
6–9	Mono, Calif.*	Mono Valley	520	ET-Mono Lake	1960	2	290	2,000–brine
	Mineral, Nev.*	do	80					
6–10	Mono, Calif.	Adobe Lake Valley	160	ET-Adobe Lake	1962	4	10	130–280
6–11	do	Long Valley	260	Lake Crowley	1954	8	25	90–1,500
6–13	Inyo, Calif.	Centennial (Black Springs) Valley.	130	GW to 6–12	1954	--	--	360
6–15	do	Deep Springs Valley	100	ET-Deep Springs Lake	1955	4	235	--
6–16	do	Eureka Valley	410	ET-playa	1955	1	115	550
6–17	do	Saline Valley	540	ET-Salt Lake	1955	1	15	3,700–brine
6–18	Inyo and San Bernardino, Calif.	Death Valley	3,420	ET-Badwater	1961	7	305	550–brine
6–19	San Bernardino, Calif.	Wingate Valley	180		1953	--	--	660
6–20	Inyo, Calif.*	Middle Amargosa basin	1,350	ET-playa	1962	20	145	300–2,900
6–21	San Bernardino, Calif.	Lower Kingston (Valjean) Valley.	750	GW to 6–18	1954	1	No water to 130 ft	5,300–8,600
6–22	do	Upper Kingston (Shadow) Valley.	700	GW to 6–21	1961	10	120	340–1,100
6–23	do	Riggs Valley	260	GW to 6–21	1954	1	45	1,740
6–24	do	Red Pass Valley	390	ET-Red Pass Lake	1944	1	115	--
6–25	do	Bicycle Valley	310	ET-Bicycle Lake	1955	1	135	610–brine
6–26	do	Avawatz Valley	180	ET-Drinkwater Lake		--	--	--
6–27	do	Leach Valley	180	ET-Leach Lake	1917	--	--	300–700
6–29	Inyo, San Bernardino, Calif.	Mesquite Valley	310	ET-Mesquite Lake	1959	22	335	300–6,300
6–30	San Bernardino, Calif.*	Ivanpah Valley	780	ET-Ivanpah Lake	1960	19	260	290–2,200
6–31	San Bernardino, Calif.	Kelso Valley	960	GW to 6–33	1961	2	195	250–750
6–32	do	Broadwell Valley	310	ET-Broadwell Lake	1883	1	330	470–1,260
6–33	do	Soda Lake Valley	1,530	ET-Soda Lake GW to 6–34.	1961	20	150	240–3,400
6–34	do	Silver Lake Valley	100	ET-Silver Lake GW to 6–23.	1954	3	55	1,100–1,740
6–35	do	Cronise Valley	390	ET-Cronise Lake	1961	13	230	450–3,100
6–36	do	Langford Valley	130	ET-Langford Lake	1958	7	160	470–640

TABLE 1.—*Undeveloped ground-water reservoirs (withdrawals less than 8,100 acre-feet (10 million m^3) per year)*—Continued

State No.	County	Ground-water reservoir	Estimated area (km^2)	Natural outflow	Exploration data: Year	Number of wells	Depth explored (m)	Range in dissolved solids (mg/l)
		South Lahontan subregion—Continued						
6–37	do	Coyote Lake Valley	390	ET-Coyote Lake	1961	5	175	300–2,500
3–38	do	Caves Canyon Valley	260	GW to 6–33	1961	5	65	200–1,300
6–39	do	Troy Valley	340	ET–Troy Lake	1961	20	120	280–6,500
6–43	do	El Mirage Valley	310	GW to 6–42	1961	75	295	320–2,600
6–49	do	Superior Valley	440	ET-Superior Lake	1956	25	115	360–2,300
6–50	do	Cuddeback Valley	340	ET-Cuddeback Lake	1956	30	90	370–4,700
6–51	do	Pilot Knob Valley	520	GW to 6–58	1918	1	--	400
6–55	Inyo, Calif.	Coso Valley	130	GW to 6–54	1946	1	35	----------
6–56	do	Rose Valley	160	ET-playa		6	55	150–1,300
6–57	do	Darwin Valley	180		1954	3	75	350–750
6–58	do	Panamint Valley, Brown Mt. Valley (6–76).	930	ET-Panamint Lake	1955	3	300	780–brine
6–71	San Bernardino, Calif.	Lost Lake Valley	100	ET-Lost Lake	1953	0	--	360
6–79	Inyo and San Bernardino, Calif.	California Valley	210	ET-playa	1953	2	15	350–500
		Colorado Desert subregion						
		Closed Basins:						
7–1	San Bernardino, Calif.	Lanfair Valley	730	GW to 7–2	1952	18	270	230–2,000
7–2	do	Fenner Valley	1,860	GW to 7–7	1952	5	285	280–870
7–3	do	Ward Valley	1,990	ET–Danby Lake	1952	2	315	330–brine
7–5	Riverside, Calif.	Chuckwalla Valley	2,250	ET-Palm Lake	1952	10	185	270–brine
7–6	do	Pinto Basin	800	GW to 7–5	1937	3	170	120–830
7–7	San Bernardino, Calif.	Cadiz Valley	1,110	ET-Cadiz Lake	1910	1	105	610–brine
7–8	do	Bristol Valley	1,840	ET-Bristol Lake	1910	8	695	290–brine
7–9	do	Dale Valley	670	ET-Dale Lake	1952	10	--	1,060–brine
7–10	do	Twentynine Palms Valley, Copper Mt. Valley (7–11), Warren Valley (7–12).	960	GW to 7–9	1952	50	150	100–1,180
7–13	do	Deadman Valley, Ames Valley (7–16).	750	GW to 7–10	1952	35	--	180–600
7–14	do	Lavic Valley	100	ET-Lavic Lake	1917	1	40	1,680
7–15	do	Bessemer Valley	180	ET-Galway Lake		--	--	--------
7–17	do	Means Valley	100	ET-Means Lake		1	--	--------
7–18	do	Johnson Valley	360	GW to 7–17	1952	1	45	340–610
7–22	Imperial, Calif.	West Salton Sea basin	750	Salton Sea	1950	3	--	2,260–brine
7–23	do	Clark Valley	100	ET-Clark Lake		--	--	--------
7–25	San Diego, Calif.	Ocotillo Valley	210	GW to 7–30	1952	6	65	700
7–27	do	San Felipe (Earthquake) Valley.	160	San Felipe Creek	1952	3	--	1,060
7–28	do	Vallecito and Carrizo Valleys.	310	GW to 7–30		--	--	----------
7–29	Imperial, Calif.	Coyote Wells Valley	260	GW to 7–30	1948	6	50	440–8,700
7–30	do	Imperial Valley	4,840	Salton Sea		80	335	690–7,500
7–31	Riverside, Calif.	Orocopia Valley	360	GW to 7–21	1952	--	--	350–1,500
7–32	do	Chocolate Valley	310	GW to 7–33		--	--	350–brine
7–33	Riverside and Imperial, Calif.	East Salton Sea basin	1,170	Salton Sea	1952	4	100	350–3,850

concerned chiefly or at least partly with collection, distribution and use, or contracting for surface water. Some water agencies are made up entirely of ground-water users, but several of these were organized to import supplemental supplies. The districts may include all or parts of ground-water reservoirs suitable for an effective program either of ground-water management or of conjunctive use of surface and ground water.

Ground-water management may involve the programming of withdrawals in space and time, the use and maintenance of barriers, and (or) artificial recharge of the reservoir. It is likely to be one aspect of overall water-management that involves conjunctive use of ground water and surface water, amelioration and maintenance of water quality, and disposal of undesirable and waste waters and soluble materials. In an area of natural water deficiency, effective water management is likely to require importation from areas of surplus; the major metropolitan areas have long been importers of water, and the principal purveyors of water from areas of surplus to areas of deficiency are State and Federal agencies.

PROBLEMS ASSOCIATED WITH USE OF GROUND WATER

A simple but very general problem of discharging wells is commonly called "falling water tables." All water discharged from a well must be balanced by a loss of water somewhere, and this loss is always to some extent, and may be largely, from storage in the aquifer (Theis, 1940). Thus some depletion of ground-water storage is an inevitable result of exploitation. Eventually the water withdrawn from the aquifer may be replaced by an equivalent amount of water of suitable quality, or the withdrawals from the well may cause increased recharge to the aquifer or decreased natural discharge from it so that the discharging well becomes a part of a new steady-state equilibrium. On the other hand, if anything else moves into the space dewatered

TABLE 2.—*Developed ground-water reservoirs*

[From Bader (1969) and California Region Framework Study Committee (1971), revised and updated]

State No.	County	Ground-water reservoir	Area (km^2)	Aquifer		Withdrawals from wells		
				Depth zone (m)	Usable capacity (km^3)	Year	Pumpage (10^6m^3)	Range in dissolved solids (mg/l)[1]
North Coastal subregion								
		Smith River Basin:						
1–1	Del Norte, Calif.	Smith River plain	180	3–11	0.09	1968	7	30–200
		Klamath River Basin:						
0–2	Klamath, Oreg.	Sprague River valley	440	----	----	1970	31	80–230
0–3	do.	Swan Lake Valley	120	----	----	1970	31	80–270
0–4	do.	Yonna Valley	120	----	----	1970	16	110–270
0–8	do.	Lower Klamath River valley	490	----	----	1970	100	130–880
1–2	Siskiyou, Calif.	do.	410	----	----	1954	12	80–830
		Closed basin:						
1–3	do.	Butte Valley	470	----	----	1953	26	110–1,900
		Eel River and Mad River basins:						
1–9	Humboldt, Calif.	Eureka plain, Mad River valley (1–8), Eel River valley (1–10).	600	3–12	.15	1962	18	50–2,000
San Francisco Bay subregion								
		Russian River basin:						
1–15	Mendocino, Calif.	Ukiah Valley	180	3–15	0.04	1954	12	110–1,120
1–18	Sonoma, Calif.	Santa Rosa Valley and Healdsburg area.	470	3–60	1.2	1954	22	90–800
		San Francisco Bay:						
2–	do.	Petaluma Valley	340	3–60	.25	1958	2	110–4,800
2–2.01	Napa, Calif.	Napa Valley	210	3–60	.30	1950	7	100–5,000
2–2.02	Sonoma, Calif.	Sonoma Valley	100	5–60	.05	1950	2	130–2,800
2–3	Solano, Calif.	Suisan-Fairfield Valley	670	3–60	.05	1949	10	300–1,350
2–4	Contra Costa, Calif.	Pittsburg plain	100	30–60	----	1931	10	480–2,060
2–5	do.	Clayton Valley, Ygnacio Valley (2–6).	160	6–60	.15	1930	10	210–2,170
		Santa Clara Valley:						
2–9	Santa Clara, Calif.	South Bay	830	8–60	.95	1969	220	240–960
	Alameda, Calif.	East Bay	470	----	----	1970	50	300–7,000
2–10	do.	Livermore Valley, Sunol Valley (2–11), San Ramon Valley (2–7).	570	8–60	.25	1970	25	290–2,800
Central Coastal subregion								
		Soquel Creek basin:						
3–1	Santa Cruz, Calif.	Soquel-Aptos area	260	----	----	----	----	180–700
		Pajaro River basin:						
3–2	do.	Pajaro Valley	360	6–90	0.03	1969	65	170–1,500
3–3	Santa Clara, Calif.	Llagas Valley	210	----	----	1969	60	250–550
	San Benito, Calif.	Hollister Valley	670	6–60	1.0	1960	135	280–2,550
		Salinas River basin:						
3–4.01 to 3–4.05	Monterey, Calif.	Salinas Valley	1,810	6–60	1.6	1960	370	240–3,000
3–4.06	San Luis Obispo, Calif	Paso Robles	2,330	15–75	2.1	1967	55	--------
		Santa Maria River basin:						
3–11	do.	Arroyo Grande Valley	100	30–240	.15	1967	20	200–2,900
3–12	Santa Barbara, Calif.	Santa Maria Valley	520	6–60	1.2	1967	140	230–3,200
3–13	do.	Cuyama Valley	600	----	.5	1967	80	400–5,000
		San Antonio Creek basin:						
3–14	do.	San Antonio Creek valley	230	----	.35	1967	14	300–3,000
		Santa Ynez River basin:						
3–15	Santa Barbara, Calif	Santa Ynez River valley	670	6–75	1.2	1967	50	400–2,000
		Santa Barbara Coastal basins:						
3–17	do.	Santa Barbara basin, Goleta Basin (3–16), Carpinteria Basin (3–18).	100	15–75	.2	1967	9	340–1,400
South Coastal subregion								
4–4	Ventura, Calif.	Santa Clara River Valley	1,190	----	0.75	1951	----	270–4,700
		Los Angeles River and Santa Ana River basins:						
4–11	Los Angeles, Calif	Coastal plain	1,300	WT–370	4.9	1970	350	140–1,340
		Central Basin	(600)	----	----	1970	(275)	--------
		West Basin	(410)	----	----	1970	(75)	--------
4–12	do.	San Fernando Valley	520	----	----	1970	135	220–2,130
4–13	do.	San Gabriel Valley	520	0–490	11.	1965	250	110–1,000
		Raymond Basin	(100)	6–460	1.2	1961–69	35	150–700
4–14	San Bernardino, Calif.	Upper Santa Ana Valley	1,680	----	----	1965	630	100–1,000
		Bunker Hill–San Timoteo.	540	----	2.1	----	----	--------
		Chino-Riverside	1,110	6–210	6.8	----	----	--------
8–1	Orange, Calif.	Coastal Plain	930	----	----	1970	240	200–2,000
		San Jacinto River basin:						
8–5	Riverside, Calif.	San Jacinto basin	650	----	----	----	----	280–3,900
		Santa Margarita and adjacent basins:						
9–4	San Diego, Calif.	Lower Valley, San Mateo (9–2), San Onofre (9–3).	60	2–msl	.07	1966	11	180–1,600
9–5	do.	Temecula Valley, Warner Valley (9–8).	100	----	.65	1961	12	250–5,000
		San Luis Rey basin:						
9–7	do.	San Luis Rey Valley	100	6–35	.06	----	----	300–9,000

TABLE 2.—*Developed ground-water reservoirs*—Continued

State No.	County	Ground-water reservoir	Area (km²)	Aquifer: Depth zone (m)	Aquifer: Usable capacity (km³)	Withdrawals from wells: Year	Withdrawals from wells: Pumpage (10⁶m³)	Withdrawals from wells: Range in dissolved solids (mg/l)[1]
		South Coastal subregion—Continued						
		San Dieguito River basin:						
9–12	do	San Dieguito area, Escondido area (9–9), San Pasqual Valley (9–10).	210	----	----	--	----	250–5,000
		San Diego River basin:						
9–15	do	San Diego area, El Cajon (6–16).	130	3–35	.12	----	----	160–4,500
9–8	do	Warner Valley	100	6–65	.07	----	----	150–420
		Central Valley subregion						
		Sacramento River basin:						
5–15	Lake, Calif.	Kelseyville Valley, Upper Lake (5–13), Scott Valley (5–14), Burns Valley (5–17).	130	3–30	0.09	1951	17	80–660
5–6	Shasta, Calif	Redding basin	1,300	6–60	.15	1955	----	120–1,700
5–21	Several (Calif.)	Sacramento Valley	11,000	6–60	35	1964	3,080	110–2,800
		Mokelumne area:						
5–22	San Joaquin, Calif.	Delta	3,110	----	----	1966	1,230	300–3,500
		San Joaquin River basin:						
5–22	Several (Calif.)	San Joaquin Valley	13,000	6–60	69	1966	8,010	90–5,000
		Tulare closed basin:						
5–22	Kern, Kings, and Tulare, Calif.	Tulare Basin	11,700	6–60	46	1966	3,700	120–2,400
		South Lahontan subregion						
		Closed basins:						
6–12	Inyo and Mono, Calif.	Owens Valley	2,230	----	----	1970	40	100–brine
6–40	San Bernardino, Calif.	Lower Mojave River valley	780	0–90	5.8	1963	85	190–2,340
6–41	do	Middle Mojave River valley	1,090	0–90	11	1963	75	140–3,900
6–42	do	Upper Mojave River valley	1,550	0–90	9.9	1963	55	80–2,760
6–44	Kern and Los Angeles, Calif.	Antelope Valley	4,140	6–60	6.7	1960	380	120–7,700
		Divided basin:						
5–27		Cummings Valley:						
5–28	Kern, Calif.	Tehachapi Valley West,	130	----	----	1961	20	350–570
6–45		Tehachapi Valley East.						
		Closed basins:						
6–46	do	Fremont Valley	850	----	----	1958	40	350–brine
6–47	San Bernardino, Calif.	Harper Valley	1,320	6–65	8.6	1963	15	320–10,700
6–52	Inyo and San Bernardino.	Searles Valley	650	----	----	1962	6	8,000
			100	----	----	1962	12	350,000
6–54	Inyo, Kern, and San Bernardino.	Indian Wells Valley	1,350	6–65	.89	1968	15	140–brine
		Colorado Desert subregion						
		Closed basins:						
7–19	San Bernardino	Lucerne Valley	830	----	----	1952	20	340–5,000
7–21	Riverside	Coachella Valley:						
		Upper valley	620	WT–20	4.4	1958	55	149–1,000
		Artesian basin	520	----	----	----	130	750–3,200
7–24	San Diego	Borrego Valley	260	3–60	----	----	12	290–1,480

[1]Includes the range in dissolved-solids concentration in observation wells of the California statewide water quality monitoring program.

by pumping from wells, the problem may become more complicated and aggravating. Removal of water from unconsolidated sediments may induce compaction of the sediments, resulting in subsidence of the land surface. In coastal areas pumping may create gradients favorable to encroachment of seawater into freshwater aquifers, and in areas where freshwater aquifers are in proximity to saline or polluted water—in lakes, playas or deep underground—withdrawal of freshwater may induce flow of saline or polluted water into the aquifer.

Numerous problems are caused by the variety of uses of water by mankind. Water used for washing, processing, cooking, or drinking may subsequently enter a ground-water reservoir with any soluble material it has acquired during the nonconsumptive use, including solid wastes, fertilizers, pesticides, herbicides, or other chemicals that could create a polluting effect. Problems may also develop with the disposal of brines and other byproducts in the production of petroleum or the disposal of soluble salts, minerals, or fuels.

DEPLETION OF STORAGE

Although depletion of storage is an inevitable result of taking water from a well, replenishment may come from precipitation or streamflow or both, or in fact not at all, as shown for example by the long-term graphs of figure 5. The variations from year to year in rainfall and runoff have induced varying responses in the water levels of four wells in southern California.

In the Williams well in Upper Santa Ana Valley

TABLE 3.—*Summary of the ground-water reservoirs listed in tables 1 and 2*

Subregion	Undeveloped ground-water reservoirs (table 1)		Developed ground-water reservoirs (table 2)			
	Number	Estimated area (km²)	Number	Area (km²)	Usable capacity[1] (km³)	Annual pumpage (km³)
North Coastal	6	2,300	7	2,800	--	0.2
San Francisco Bay	1	100	9	4,000	3	.4
Central Coastal	1	700	10	7,900	9	1.0
South Coastal	0	----	13	7,800	26	1.7
Coastal basins	8	3,100	39	22,500	38	3.3
Tributary valleys	7	2,300	2	1,400	--	--
Sacramento Basin	--	----		10,800	--	3.1
Delta area	--	--	1	3,100	--	1.2
San Joaquin Basin	--	----		13,000	--	8.0
Tulare Basin	--	----		11,300	-	3.7
Central Valley	7	2,300	3	39,600	125	16
North Lahontan	3	3,400	0	----	--	--
South Lahontan	38	18,800	10	14,100	43	0.7
Colorado Desert	23	22,200	3	2,200	4	.2
Interior basins	64	44,400	13	16,300	47	0.9
Total	79	50,000	55	78,000	210	20

[1]Estimates of usable capacity have been made for only 37 of the 55 ground-water reservoirs listed, and these represent the investigators' judgment of what is technically and economically practical at the time.

(State Basin No. 4–14 on pl. 1), the water level declined 40 feet (12 m) or more during each of the drought periods 1895–1904 and 1924–36 but recovered during the subsequent wetter periods 1905–23 and 1937–45. Since 1945 the water level has declined nearly 165 feet (50 m), interrupted by temporary rises caused by exceptional recharge in that part of the reservoir during the wet years 1952, 1958, and 1969. In this valley artesian supplies were once so abundant that San Bernardino County was exempted from the State law enacted in 1878 prohibiting waste from flowing wells.

The well on the Oxnard Plain (Basin No. 4–4) indicates reduction in storage during the dry years that have been prevalent since 1945, and full replenishment during years of abundant runoff such as 1952, 1958, 1967, and 1969.

Another hydrograph in figure 5 is a composite record of two wells in Antelope Valley (Basin No. 6–44), which also had an extensive area of artesian flow and more than 200 flowing wells prior to 1908. By 1920 there were 250 pumped wells, and records available since 1922 indicate increasing pumping and a continuous decline of water levels in wells, not only throughout the drought of 1924–36 but during the subsequent wet years 1937–45 and continuing today. By 1946 the decline throughout the pumping district was at an average rate of 3 feet (1 m) a year, prompting the State Legislature to call for a survey. The report of that survey (Gleason, 1947) showed that pumpage exceeded recharge even in the wet years 1944 and 1945 and forecast it would exceed the recharge by more than 50,000 acre-feet (60 million m³) in 1947, and by greater amounts in subsequent years with expansion of irrigated acreage. For a quarter of a century, water levels have declined as predicted, at rates of 3 feet (1 m) or more per year in the pumping districts (Snyder, 1955; Powers, 1970).

In the Central Valley, the annual pumpage from wells has exceeded 12 million acre-feet (15 km³) for several years. In many parts of the valley, the water withdrawn has been replenished within months by infiltration of precipitation and surface water; in other areas replenishment has been ample in years of abundant precipitation and streamflow but not in years of drought; in some areas of the Central Valley pumping has caused progressive decline of water levels in wells and depletion of ground-water storage.

The principal areas of storage depletion in the Central Valley are outlined in figure 6. Those in the Sacramento Valley appear as composite cones of depression where pumping has lowered water levels by 30–80 feet (10–25 m), and the depressions extend below sea level; these areas of depletion are in the interstream areas between major tributaries flowing from the Sierra Nevada. Similar closed depressions are found between the Sierra streams entering the southern part of the Central Valley; they generally do not extend down to sea level, but the largest—between the Kings River and Kern River—is more than 65 feet (20 m) deep and has a length of about 125 miles (200 km). The most formidable decline in water levels, however, has been caused by pumping from the confined aquifers underlying the western part of San Joaquin Valley. Here, water levels are below sea level throughout an area extending from Tulare Lake northwestward 90 miles (140 km) toward Los Banos; in numerous wells they are more than 200 feet (60 m) below sea level. (See section "Land Subsidence.")

The depressed areas in the Central Valley, as in Antelope Valley, are noteworthy because water levels have declined more than 100 feet (30 m) under extensive areas, indicating considerable depletion. Water levels reached record lows in many wells during the 1960's, especially in 1961 and 1966, which were the driest of the decade, and were rising during the wetter years 1969 and 1970, although water levels continued to decline in areas near Sacramento and Stockton and in the southern part of the Tulare Basin (California Department of Water Resources, 1971a). In several irrigation districts in the Tulare Basin, however, water levels in wells have risen more than 65 feet (20 m) since 1951, following the arrival and availability for irrigation of water in the Friant-Kern Canal.

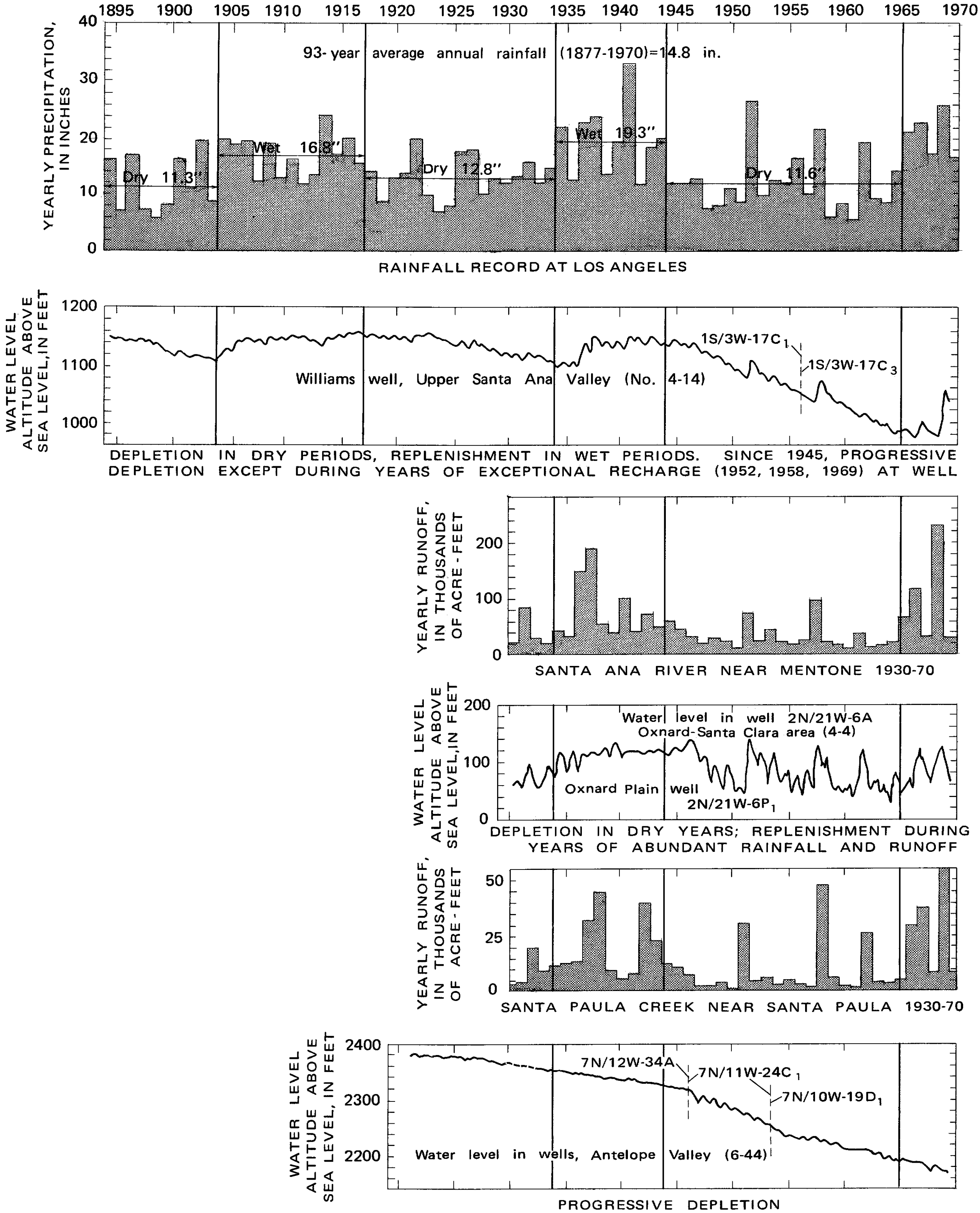


FIGURE. 5.—Effects of pumping and recharge on water levels in wells in southern California.

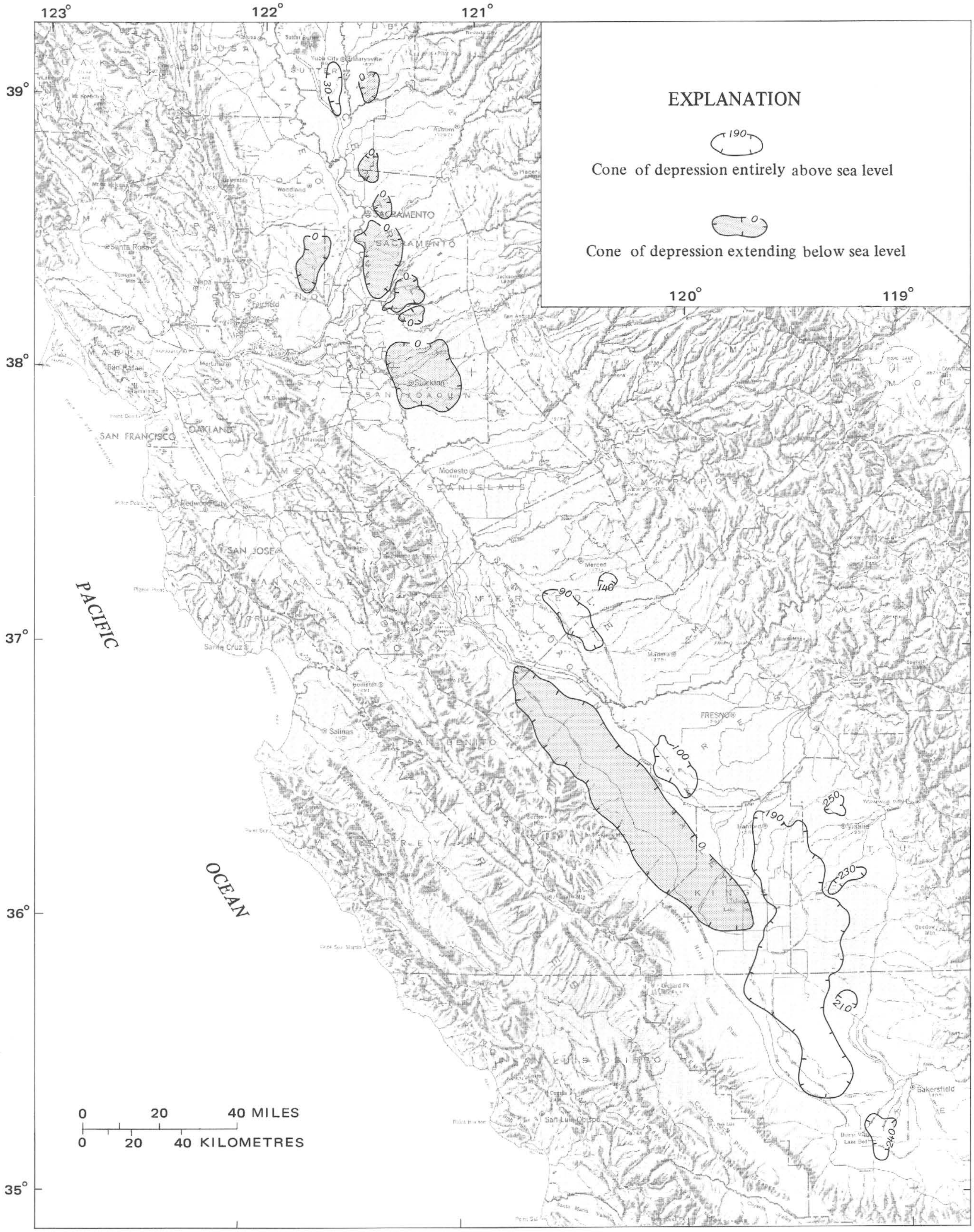


FIGURE 6.—Cones of depression caused by pumping from wells in the Central Valley.

In some ground-water reservoirs, depletion of storage has created other problems, as exemplified by the coastal plain (Basin No. 8–1) in Orange County (fig. 7). In 1944, after several wet years, the potentiometric surface had a natural gradient toward the ocean, with two small depressions caused by pumping near the coast. Ten years later the water levels in wells had declined moderately 10–30 feet (3–9 m), and then were below sea level under practically all the coastal plain. Thus the reservoirs were opened to seawater intrusion. (See section "Seawater Intrusion.")

LAND SUBSIDENCE

Significant land subsidence due to withdrawal of ground water has occurred in areas totaling about half of San Joaquin Valley (State Basin No. 5–22 on pl. 1) and half of Santa Clara Valley (No. 2–9) at the south end of San Francisco Bay. In Antelope Valley (No. 6–44), releveling indicates subsidence as great as 3 feet (90 cm). These areas of subsidence overlie confined aquifer systems in which the artesian head has been drawn down more than 100 feet (30 m) and in places more than 325 feet (100 m). The aquifer systems contain permeable sand and gravel interbedded with and overlain by silty and clayey materials which become compacted as water is pumped out, and the land surface sinks. The water squeezed out by compaction is permanently withdrawn, but because compaction of the permeable beds is slight, the effect upon the usable capacity of the aquifers is negligible. Subsidence may be occurring in other areas of pumping from confined aquifers in the California Region, but it is not sufficient to be observed without releveling.

In Santa Clara Valley, releveling in 1933 to bench marks in San Jose produced evidence—the first in the United States—of subsidence caused by ground-water withdrawal. As summarized by Poland (1969), land subsidence occurred where pumping drew down the artesian head in the confined aquifer system, but not where the water was unconfined. The subsidence ceased during the wet period 1936–43, when water levels rose as much as 80 feet (25 m), and resumed in 1948 after the artesian head declined below the 1935 minimum. The volume of land subsidence from 1934 to 1967 is computed to have been half a million acre-feet (0.6 km^3), equivalent to about 10 percent of the total pumpage in the 33-year period. Water imported from the Central Valley through the State's South Bay aqueduct became available in 1965, and annual imports increased to more than 120,000 acre-feet (150 million m^3) by 1970. As a result of the increasing imports and decreasing pumping, plus increased natural and artificial recharge, the artesian head in more than a hundred wells rose an average of about 56 feet (17 m) from 1967 to 1970, and the land subsidence practically ceased; nevertheless, no rebound, or aquifer expansion, took place. Records of subsidence in relation to water-level trends, pumpage, and imports in Santa Clara Valley are given in figure 8.

San Joaquin Valley has three principal areas of land subsidence due to ground-water withdrawals (Poland and others, 1973), the largest encompassing about 1,500 square miles (4,000 km^2) along the west slope of the valley between Los Banos and Kettleman City (fig. 9). Thousands of irrigation wells, many yielding more than 1,500 acre-feet (1.8 million m^3) a year, pump water from confined aquifers 300–3,000 feet (90–900 m) deep and have caused water levels to decline as much as 450 feet (140 m). The maximum subsidence exceeded 28 feet (8.5 m) by 1970; because the volume of subsidence was more than 8.1 million acre-feet (10 km^3) and the estimated gross pumpage about three times as great, approximately one-third of the water withdrawn has been derived from compaction of sediments.

In the Tulare-Wasco area of about 800 square miles (2,100 km^2), pumping from 1930 to 1951 caused as much as 10 feet (3 m) of subsidence, while water levels declined 230 feet (70 m). After importation of water through the Friant-Kern Canal began in 1951, pumping decreased in parts of the area, and by 1970 land subsidence had virtually ceased in about one-third of the area. In the Arvin-Maricopa area at the south end of San Joaquin Valley, at least 400 square miles (1,000 km^2) of irrigated land has subsided at rates of as much as 0.5 foot (15 cm) a year, and subsidence is continuing. This subsidence also is caused by pumping from wells in confined and semi-confined aquifers, chiefly since 1940, which has caused water levels to fall 3–13 feet (1–4 m) a year and as much as 400 feet (120 m) since 1929.

For all of San Joaquin Valley, the volume of subsidence, and therefore the reduction in pore space caused by ground-water depletion, exceeded 11 million acre-feet (13½ km^3) by 1966.

Not all the land subsidence in the Central Valley is related to ground-water withdrawal. Subsidence in some areas has occurred where the soil had never been thoroughly dry and in other areas where the soil had never been thoroughly wet until man came along with his reclamation of lands for agricultural use (Poland and Evenson, 1966, p. 244). The wetlands were in the delta at the confluence of the Sacramento and San Joaquin Rivers, where islands have been drained for cultivation and protected by levees; with the lowering of the water table, the organic soils have subsided 6–15 feet (2–5 m) because of drying, oxidation, shrinking, and wind erosion. At the other extreme, the drylands are the clayey alluvial-fan soils along the west side of the San Joaquin Valley, which have been moisture deficient ever since their deposition and which have subsided

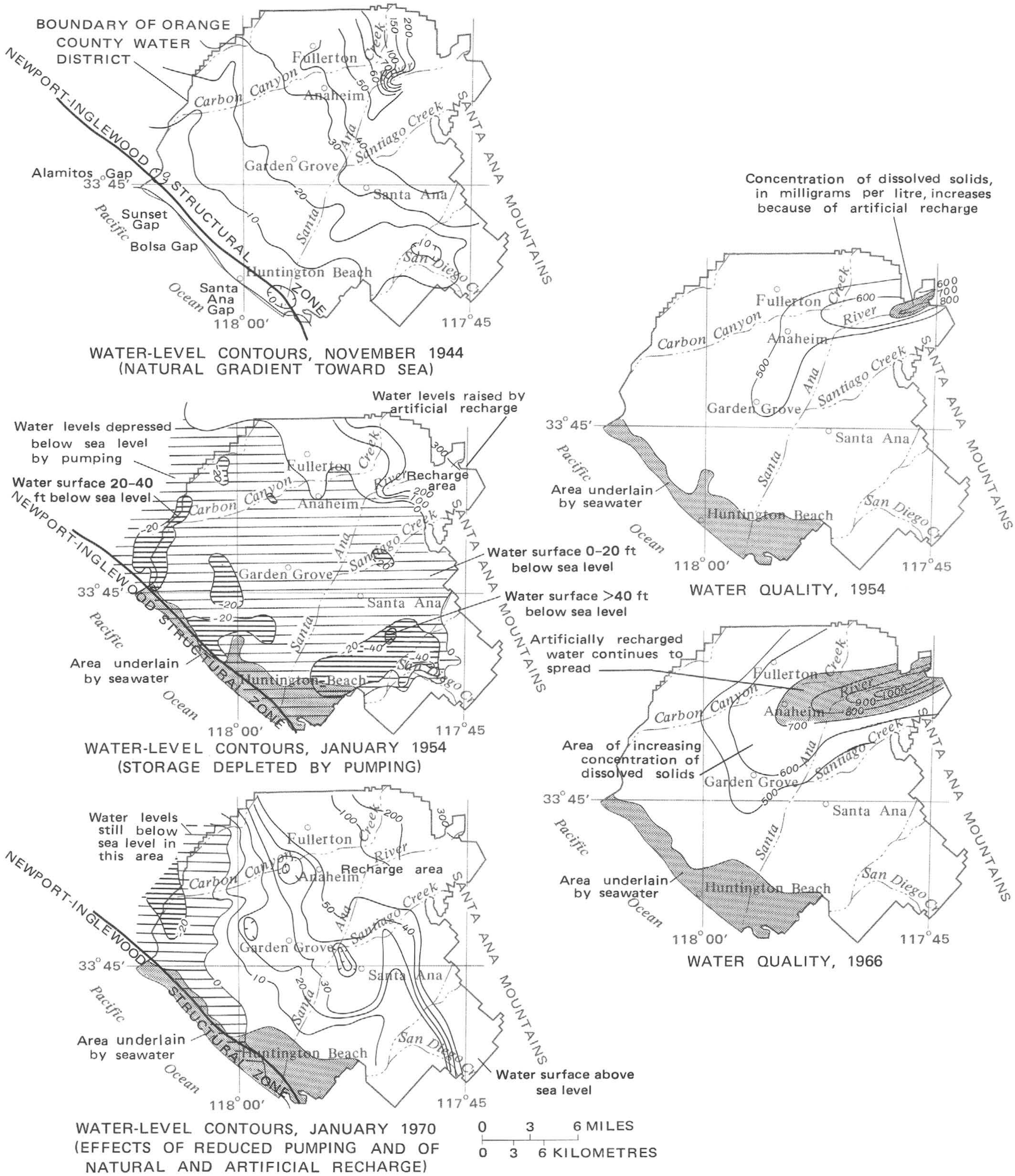


FIGURE 7.—Depletion and recovery of ground-water storage, Orange County coastal plain.

3–15 feet (1–5 m) in response to the first irrigation of the land.

Subsidence has caused failure of many wells owing to rupture of casings by the compaction. Also, subsidence

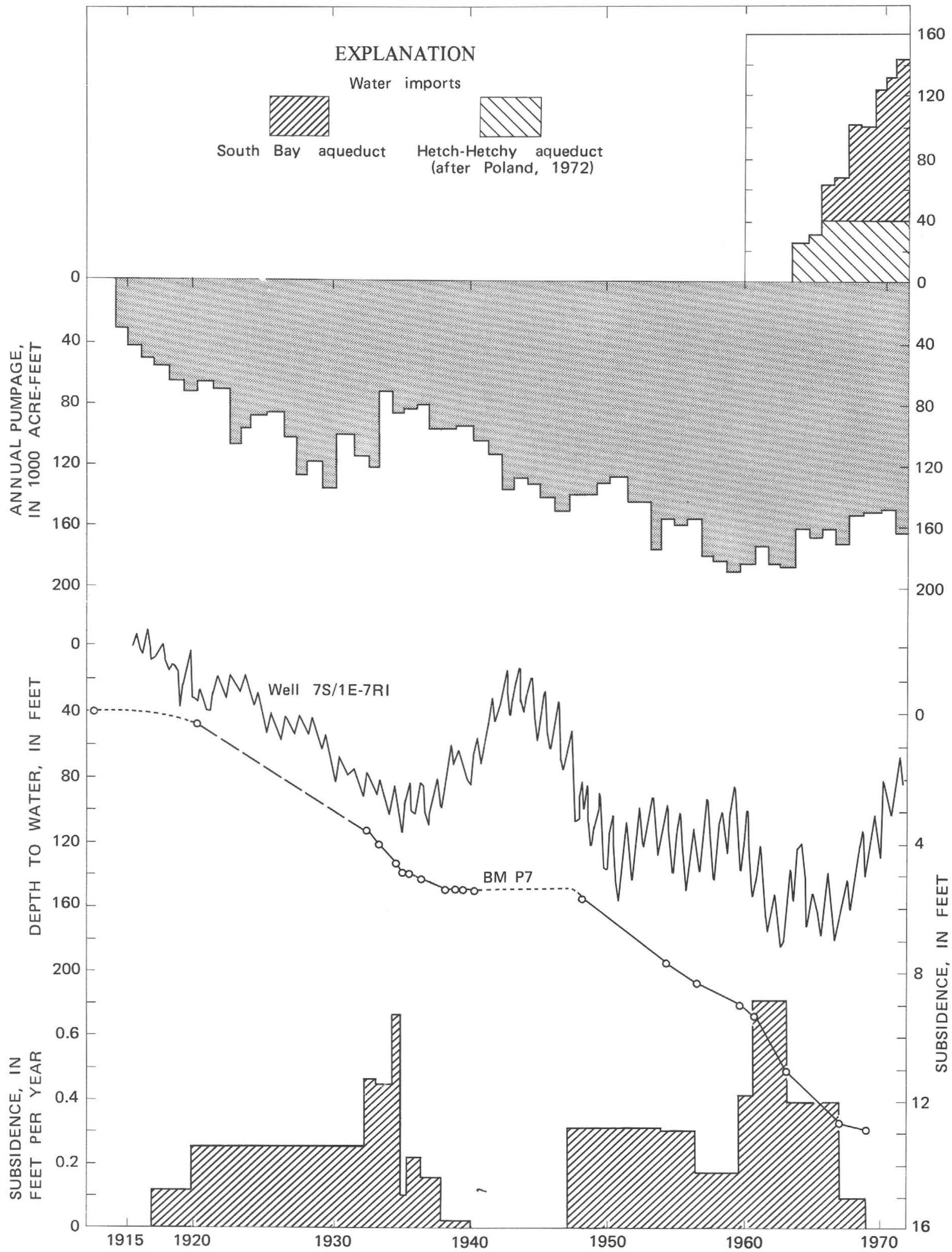


FIGURE 8—Pumpage and imports of water in Santa Clara Valley and correlative water-level changes and land subsidence, 1915–70.

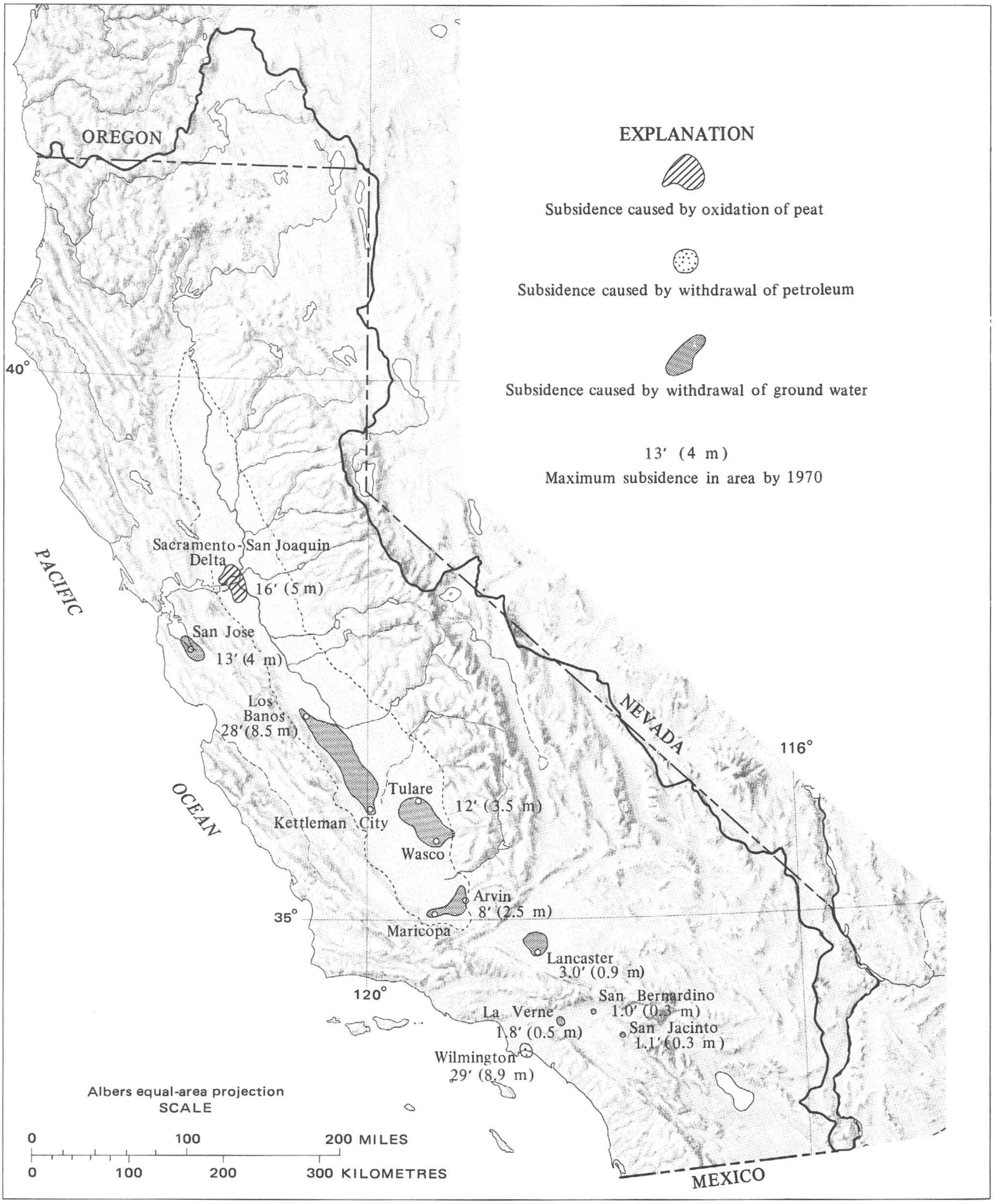


FIGURE 9—Areas of land subsidence in the California Region.

may increase the difficulty or expense of using the land, particularly along the seacoast if the land subsides below sea level.[3] However, the subsidence of Santa Clara Valley, although exceeding 10 feet (3 m) at some places, was less than 3 feet (1 m) along the south shore of San Francisco Bay. This made wetlands wetter, deepened the water in sloughs and channels entering the bay, and reduced the gradient and gravity flow of drains and pipes discharging into the bay.

The subsidence caused by ground-water depletion is generally slight in comparison to the breadth of area involved, and residents may be unaware of any change except as shown by releveling. Subsidence has probably occurred in several valleys in California where water levels have been lowered tens of feet, but has been noticed only where it disturbed canals or pipelines. For example, the Metropolitan aqueduct has dropped as much as 3 feet (1 m) near La Verne in San Gabriel Valley Basin (No. 4–13), and the San Diego aqueduct has dropped 1 foot (30 cm) near San Jacinto in San Jacinto Valley Basin (No. 8–5) (Miller and Singer, 1971).

In San Joaquin Valley the area of greatest subsidence is not in the trough of the valley, where it might affect the drainways of Fresno Slough and San Joaquin River, but along the west slope where streamflow is ephemeral. Here, both the Delta-Mendota Canal and the Friant-Kern Canal have required remedial work because of subsidence. Although the California Aqueduct passes through the centers of most rapid westside subsidence, future subsidence was estimated prior to construction so that protection from anticipated subsidence could be built into the aqueduct freeboard. Pumping from wells has approached 2 million acre-feet (2½ km^3) annually along the west slope of San Joaquin Valley, and the subsidence will continue while pumping continues. Water deliveries from the aqueduct to the Federal San Luis project (in the subsiding area) have increased from 200,000 acre-feet (0.25 km^3) in 1968 to 650,000 acre-feet (0.8 km^3) in 1971, and because pumping of ground water has decreased, the artesian head in the main pumped zone had risen an average of 56 feet (17 m) by December 1970 (Poland, 1972). Upon completion of the distribution systems, a maximum of 1.2 million acre-feet (1.5 km^3) can be imported into the San Luis project area.

[3]The most spectacular land subsidence in the California Region occurred in the Long Beach harbor area (State Basin No. 4–11 on pl. 1), not because of ground-water withdrawal but because of withdrawal of oil and gas in the Wilmington oil field (Poland and Davis, 1969). First noticed in 1940, the subsidence increased by 1962 to a maximum of 27 feet (8.2 m) at its center on Terminal Island and included an area of 25 square miles (65 km^3) that had subsided 2 feet (0.6 m) or more. The cost of remedial measures such as levees and fill to keep the sea from invading the subsiding lands and the repair of several hundred oil wells had exceeded $100 million by 1962, but the value of petroleum produced was far greater. Beginning in 1958, the oil zones were repressured by injecting saline water, which stopped the subsidence in much of the field by the end of 1962, and appreciable rebound was noted at several bench marks.

In summary, research and experience in areas of significant land subsidence provide a fair understanding of the causes and processes of that subsidence. Where subsidence is caused by ground-water withdrawals, reduction or cessation of withdrawals can slow down or halt the subsidence. Both in southern San Joaquin Valley and in Santa Clara Valley, pumping from wells has been reduced as substitute supplies became available from canals, and the problem of subsidence has been alleviated.

SEAWATER INTRUSION

Seawater intrusion occurs only where conditions are favorable to landward or upward movement of seawater, conditions that develop where ground-water levels are lowered below sea level by pumping from wells. Along the California coast, 263 ground-water basins or areas, large and small, (California Department of Water Resources, 1958a) are contiguous to the sea or to saline inland bays; as of 1955, evidence of seawater intrusion was found in 11 of these. In 70 other areas the ground water near the coast was more saline than water farther inland; eight of these areas had extensive ground-water development, and pumping from wells had lowered water levels below sea level in some places so that intrusion may have been suspected but was not proved. In 48 areas pumping from wells was not known to have reversed the natural seaward ground-water gradient, and no evidence of seawater intrusion was found. In 134 minuscule ground-water basins there was nearly no ground-water development and no likelihood that the natural seaward gradient was modified.

The 11 areas where seawater intrusion was confirmed in 1955 are given in table 4, which summarizes the location, extent, source, and human response to the saline intrusion. The northermost of these sites is around San Francisco Bay, where about half the runoff from the California Region encounters seawater. Every day during high tides, ocean water enters the bay through the Golden Gate, and the bay is characteristically saline as far east as the Carquinez Straits, but during the greatest of historic floods (1862), flow was continuous out of the bay into the ocean, and San Francisco Bay had freshwater fish for several months (Harding, 1960). In Suisun Bay, east of the straits, the water flowing from the Central Valley during the 19th century was naturally fresh enough to drink. With increasing diversions for irrigation, the freshwater flow diminished, especially in dry years such as 1924 and 1931, and incursions of saline water into the channels and sloughs of the delta occurred as far upstream as Stockton and Walnut Grove. During the 1924–34 drought, wells on the Pittsburg Plain (Basin No. 2–4 on pl. 1) pumped water whose fluctuations in salinity

TABLE 4.—*Seawater intrusion in 1955*

State No.	Ground-water reservoir	Aquifer intruded: Name and depth (m)	Aquifer intruded: Area (km²)	Aquifer intruded: Distance from sea (km)	Source of seawater	Solution
	San Francisco Bay subregion					
2–1	Petaluma Valley	Shallow	4	16	Tidal channels	Affected wells abandoned.
2–2	Napa Valley, Sonoma Valley	Alluvium <30	8	19	do	Do.
2–3	Suisun-Fairfield Plain	Alluvium	81	8	do	Do.
2–4	Pittsburg Plain	Alluvium >30	32	1½	Suisun Bay	Do.
2–9	Santa Clara Valley:					
	South Bay	Shallow	243	6	San Francisco Bay	Do.
	East Bay	Newark 20–45	162	10	do	210 wells abandoned.
	East Bay	Centerville 60	12	--	Shallow aquifer	50 wells abandoned, 30 defective wells repaired.
	Central Coastal subregion					
3–2	Pajaro Valley	75	16	1½	Pacific Ocean	50 wells abandoned.
3–4	Salinas Valley	55	40	4	do	100 wells abandoned, 20 wells deepened.
3–4	do	120	16	3	do	
	South Coastal subregion					
4–4	Oxnard Plain	Oxnard 45	32	3	Pacific Ocean	45 wells abandoned; injection wells; extraction wells.
4–11	Los Angeles Coastal Plain	Gaspur 60; Silverado 120.	65	3 5	do do	Artificial recharge; freshwater ridge; reduced withdrawal.
8–1	Orange Coastal Plain	Talbert 25	40	5	do	Artificial recharge; reduced withdrawal; combination barrier.
9–7	San Luis Rey Valley	<30	.8	--	Tidal channel	Artificial recharge.

correlated with those in a nearby slough of the Sacramento River (Tolman and others, 1931). The Contra Costa Canal now supplies water for industrial use in this area, and most of the wells are no longer in service. Farther west, along the north shore of the bay in Napa, Sonoma, and Petaluma Valleys (Basins Nos. 2–1, 2–2), seawater has intruded into pumped aquifers by infiltration of surface water in tidal channels, rather than by subsurface inflow from the bay.

In Santa Clara Valley along the south arm of San Francisco Bay, intrusion of salt water has been sufficiently widespread to cause abandonment of most wells in the shallow aquifer, but numerous shallow wells still yield usable water, indicating that the aquifer is heterogeneous in water quality as well as permeability characteristics. East of the bay in the vicinity of Niles and Hayward, saline water has evidently advanced 2–5 miles (3–8 km) into the shallow (Newark) aquifer on a broad front. The deterioration of quality in the deeper (Centerville) aquifer is spotty and has been attributed to faulty or abandoned wells that bring water from the Newark aquifer or to leakage through the separating aquicludes (California Department of Water Resources, 1960a, 1968d). At several of the monitored wells in this East Bay area, the salinity of water increased progressively during the 1960's, and the area of degraded water in the Centerville aquifer expanded slightly during 1970 (Alameda County Water District, 1971). The total pumpage in 1970, however, was about 15 percent less than the average prior to 1965, and recharge has been augmented artificially since 1963. (See section "Recharge in Urban Areas.") The 1970 water levels in several observation wells were 15–65 feet (5–20 m) higher than the minimums registered in 1961 or 1962 but were still below sea level (California Department of Water Resources, 1971a).

In Pajaro Valley along the Central Coast, the variation in quality of water from well to well in the producing aquifer indicates that some saline water may enter cones of depression from tidal channels or sloughs or ponds. In the Salinas Valley the confined aquifer near the seacoast appears to include segregated lenses of fresher and saltier water, responsible for variations in quality of water from wells (California Department of Water Resources, 1949, 1970f).

In the Oxnard Plain in the South Coastal subregion, seawater intrusion continued at apparent rates of as much as 1,000 feet (300 m) a year in 1961 and 1962, especially at Port Hueneme and Point Mugu (California Department of Water Resources, 1965a). Many wells tapping the shallow (Oxnard) aquifer were abandoned in favor of wells in deeper aquifers not yet reached by seawater. The Ocean City Municipal Water District has injected water into the Oxnard aquifer through a line of wells in the "pumping trough" inland from the invading seawater (Price and Baker, 1963), using water from wells about 8 miles (13 km) farther inland; this program achieved an effect similar to rearrangement of pumping pattern, with no reduction in total withdrawal. An experimental extraction-type barrier was constructed near Port Hueneme in 1966 and operated for 2 years (California Department of Water Resources, 1970b), during which five wells extracted 9,000 acre-feet (11 million m^3) of brackish water and reduced the area underlain by degraded waters.

Along the San Luis Rey River in San Diego County where seawater intrusion was first noted in 1938 (California Department of Water Resources, 1950), the importation of water from the Colorado River has enabled the City of Oceanside and suburban agriculturists to restrict their pumping from wells, and reclaimed sewage is used to recharge the ground water; by achieving an approximate balance between recharge and discharge, the ground-water reservoir is apparently holding its own against seawater invasion, although pumping has drawn water levels below sea level in a trough 2–6 miles (3–10 km) from the ocean. Along the San Diego River salt-water encroachment from Mission Bay, noted in 1906, caused abandonment of wells in the Old Town pumping field. In the valleys of the San Dieguito and Tia Juana Rivers farther south, water levels near the coast are drawn seasonally below sea level, causing some seawater intrusion.

The coastal plain in Los Angeles and Orange Counties has been the scene of the most serious seawater intrusion and most comprehensive counter measures in the California Region. For more than half a century, the ground-water reservoir was pumped for the requirements of a progressively increasing population (Poland, 1959). By 1953, water levels in wells were below sea level in extensive areas (fig. 7), numerous wells near the coast had been abandoned because of increased salinity, and brackish water had been reported in some wells as much as 8 miles (13 km) inland (California Department of Water Resources, 1957b, 1958a). Not all the salt came from seawater, for beginning in the 1920's oil-field brines in several localities were dumped in ponds and surface channels and in some areas wells have discovered connate water. Most of the seawater intrusion has occurred west of the Newport-Inglewood zone of faulting and uplift, which generally impedes ground-water movement. This zone is less than 2 miles (3 km) from the coast in Orange County but as much as 7 miles (11 km) inland in Los Angeles County. The battle against the invading seawater is one phase of water-management activities by local agencies of countywide jurisdiction. (See section "Recharge in Urban Areas.") These agencies coordinate their anti-invasion efforts at Alamitos Gap along the county line but operate separately elsewhere.

In the coastal plain in Los Angeles County, pumpage has been reduced from 354,000 acre-feet (436.5 million m^3) in 1961 to court-limited extractions of 281,835 acre-feet (347.5 million m^3) since 1963 (Bookman and Edmonston, 1971). In 1970, however, water levels in wells reaching the main (Silverado) aquifer were still as much as 100 feet (30 m) below sea level in extensive areas, as low as they had been 10 years earlier. From 1953 to 1970, water spread for artificial recharge aggregating 1.6 million acre-feet (2 km^3) raised levels in extensive areas, but not in the West Basin, which is west of the Newport-Inglewood zone and where all the seawater intrusion has occurred.

Although the water levels in most of the West Basin are still below sea level, the sea has been repelled and cannot enter the main aquifer because of a continuous barrier ridge of freshwater created by importation of water from the Colorado River and injection in a line of 93 wells extending 11 miles (18 km) south from the Los Angeles International Airport to Palos Verdes Hills. By 1961, when 28,000 acre-feet (34.5 million m^3) had been injected into 12 wells, a wedge of invading seawater had been cut off and diluted, and in 1970, after injections had aggregated about 300,000 acre-feet (370 million m^3), water in the aquifer east of the barrier was generally of usable quality. Meanwhile, barriers are being similarly designed and developed to halt seawater invasion in Dominguez Gap east of Palos Verdes Hills and in Alamitos Gap at the Orange County line.

In Orange County most ground water seaward of the Newport-Inglewood barrier zone is saline in shallow aquifers and brackish in the main (Silverado) aquifer 200 feet (60 m) or more below sea level. Freshwater naturally moved across this barrier through Alamitos, Sunset, Bolsa, and Santa Ana Gaps, forming stream channels, alluvial aquifers, peat bogs, swamps, and marshes as it moved (California Department of Water Resources, 1968a). The direction of flow was reversed during the 1950's, when the water levels were below sea level in wells at the coast and for more than 6 miles (10 km) inland (fig. 7). As corrective measures, annual pumpage was substantially reduced, and Colorado River water was imported and spread for artificial recharge (Crooke and Toups, 1962). As of November

1970, water levels in wells were above sea level in all parts of the county except in the vicinity of Alamitos Gap, where a barrier ridge was maintained to repel further intrusion of seawater (Cofer, 1971). At the Santa Ana Gap, the county's combination barrier project (California Department of Water Resources, 1966b) includes a line of wells in the Newport-Inglewood zone about 2 miles (3 km) from the sea which extract brackish water and return it to sea and also a line of wells 2 miles (3 km) farther inland where freshwater is injected to create a barrier ridge.

In the Central Valley, a large body of saline water of marine origin underlies the freshwater aquifers of San Joaquin Valley at depths generally greater than 1,000 feet (300 m) but is as little as 400 feet (120 m) deep in the Modesto-Turlock-Waterford area, where gas wells yield water with 4,000 mg/l (milligrams per litre) dissolved solids including 2,400 mg/l chloride (California Department of Water Resources, 1960b). South of the Delta-Mendota canal near Firebaugh and Mendota, water pumped from wells has 1,700 mg/l dissolved solids, 350 mg/l chloride, and 750 mg/l sulfate. In the islands of the Delta, fresh ground water may be in lenses surrounded by brackish water at depths less than 100 feet (30 m) (California Department of Water Resources, 1965c). These may be connate waters but modified in composition during subsequent millennia so that they are different from modern seawater. In the vicinity of Stockton, many wells obtain freshwater from shallow aquifers, but studies in the 1950's (California Department of Water Resources, 1955b) indicated little or no vertical mixing of freshwater with underlying saline water. Nor was there migration of the saline water into the cone of depression formed by pumping for irrigation farther east, perhaps because of the extractions of saline water for industrial use in the western part of Stockton.

In the developed ground-water reservoirs where seawater intrusion was suspected in 1955 (fig. 10), no notable crises have developed in subsequent years. Along the North Coast, Crescent City and Eureka have freshwater in aquifers above and below sea level and salty water in sediments adjacent to bays and tidal sloughs. Wells can yield freshwater perennially from aquifers that are replenished by major rivers as they flow to the sea, although their yield will become salty if pumping induces inflow of ocean water, but this has not happened to a significant degree. Water-well standards have been recommended (California Department of Water Resources, 1966a) to minimize the vulnerability of freshwater aquifers to deterioration by water of inferior quality. Along the Central Coast some wells at Santa Cruz are close enough to the sea to be similarly vulnerable. Farther south, pumping in Arroyo Grande Valley can induce seawater intrusion, but it has not happened yet (California Department of Water Resources, 1970g).

Along the South Coast, three small ground-water reservoirs underlie narrow coastal plains in the vicinity of Santa Barbara. During the drought of 1945–55, ground-water levels were lowered below sea level in these basins; however, the reservoirs are separated from the Pacific Ocean by impermeable rocks along the coast, and thus no breakthrough of seawater occurred. With completion of Cachuma Dam on the Santa Ynez River in 1955 and deliveries of water through the Tecolote Tunnel, pumping from these ground-water reservoirs has been reduced, and they constitute reserves available whenever surface supplies are diminished unduly by drought.

The ground-water reservoir under the Lompoc Plain near the mouth of the Santa Ynez River is not known to be separated from the Pacific Ocean by any barrier. Pumping for irrigation has been greatest in years of drought and minimum streamflow, notably 1946–51 and 1959–61, but even in these years the water level in wells nearest the coast was at least 3 feet (1 m) above sea level. Water has been diverted from the Santa Ynez River basin for municipal supply in the Santa Barbara area; the ground-water reservoir gains when the Cachuma reservoir stores flood water in wet years (1958, 1962, 1969), and it is released at rates suitable for ground-water replenishment. The Santa Maria Valley farther north is similar in many respects, for it has no natural barrier to seawater intrusion and substantial pumping for irrigation has not depressed water levels below sea level. The Twichell Reservoir in the headwaters provides controlled releases of water that increase the ground-water replenishment. Thus, these ground-water reservoirs of Santa Barbara County have been rendered less vulnerable to seawater intrusion by integrated management and conjunctive use of surface-water and ground-water resources.

RESERVOIR POLLUTION

Broadly speaking, pollution and contamination have about the same meaning. The American Heritage Dictionary (1969) states: "Pollution: 1. The contamination of soil, water, or the atmosphere by the discharge of noxious substances." The laws to control pollution or protect quality of water, however, include definitions that may differentiate between pollution and contamination in order to identify human perils or human responsibilities more specifically.[4] The Federal Water

[4]The California Water Code (sec. 13050) defines pollution as "an alteration of the quality of the waters of the state by waste to a degree which unreasonably affects (1) such waters for beneficial uses, or (2) facilities which serve such beneficial uses." Contamination is defined as "impairment of the quality of waters of the state by waste to a degree which creates a hazard to the public health through poisoning or through the spread of disease."

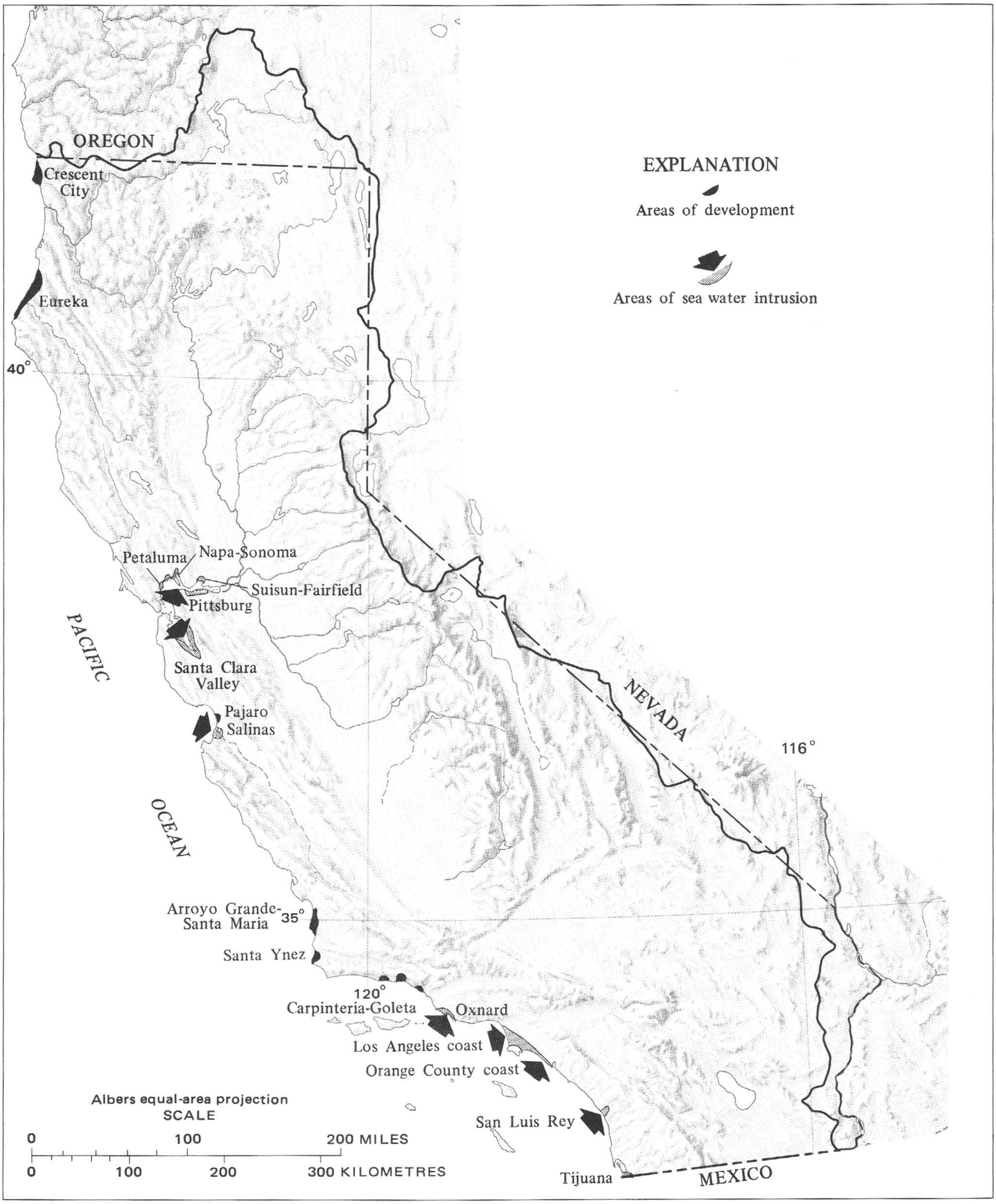


FIGURE 10.—Seawater intrusion and coastal ground-water reservoirs.

Pollution Control Act Amendment of 1972 (PL 92–500) states in its Title V, section 502:

(19) The term "pollution" means the manmade or man-induced alteration of the chemical, physical, biological, and radiological integrity of water.

(6) The term "pollutant" means dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological material, radioactive materials, rock, sand, cellar dirt, and industrial, municipal and agricultural waste discharged into water.

The Safe Drinking Water Act of 1974 (PL 93–523), included as Title XIV of the Public Health Service Act, is concerned with protection of public health from harmful impurities in water, whether manmade or man induced or natural, and it states in its section 1401: "(9) The term 'contaminant' means any physical, chemical, biological, or radiological substance or matter in water."

In this appraisal, in accordance with these definitions, "contaminants" include all impurities in water, and "contamination" is the process of "impurification," whether by act of man, act of nature, or act of God; "pollutants" are limited to the impurities for which man is responsible, and "pollution" is the process by which man contributes to deterioration of water quality.

Ground water has been polluted in many places in the California Region by improper construction, use, or abandonment of wells (United States Public Health Service, 1961), and to alleviate this problem minimum well construction and sealing standards have been published (California Department of Water Resources, 1968b). Pollution of ground-water reservoirs generally is difficult to detect or trace because of the deterioration of water quality is likely to be gradual in time and space. Also, many of the human activities and processes that cause pollution have their counterparts in natural processes that cause deterioration of water quality. Thus the identification, quantification, and description of pollution by mankind requires background knowledge of the natural deterioration of the water resources.

NATURAL DETERIORATION

Degradation is a geologic process, a general lowering of the earth's land surfaces by erosion chiefly by water of the lithosphere where it is exposed to the atmosphere. Within the range of temperatures at the earth's surface, water may exist as solid, liquid, or gas; more than 97 percent is habitually in liquid form, in the oceans, forming the hydrosphere that covers more than 70 percent of the lithosphere, and another 2 percent is solid, in polar icecaps. The process of degradation is accomplished by solar energy that evaporates water from the oceans and carries it in air currents over the continents and islands, where it falls as rain or snow upon the land surface. Then the forces of gravity may move it to run off overland or to infiltrate into the soil and percolate downward to become ground water, or to flow in streams or underground and eventually reach an ocean. In the course of this hydrologic cycle, water may break solid rock by freezing and thawing, dissolve rock materials and carry them in solution, dislodge small particles and carry them in suspension, undercut larger fragments and lubricate their downhill passage, move larger rocks along the beds of streams, and thus move the lithosphere, piece by piece and ion by ion, to lower levels and ultimately to the ocean unless epeirogenic or orogenic forces intervene.

The degradation of the continents and islands is a gradual, progressive, and inexorable process carried on by water in the hydrologic cycle. As to the water, in its plan of salvation, one part in 10,000 evaporates each year and returns to earth purified. This is the preferred water among people, because they are among the terrestrial life that has become adapted to freshwater. But in the process of degradation of the land, there is a natural deterioration of the water—by accumulation of impurities—for which man is not responsible and which is therefore not properly termed pollution.

The atmosphere habitually contains only about seven of each million molecules of the water on earth, but every year about 380 molecules per million are evaporated into the atmosphere and then dropped again as precipitation. The water of precipitation is characteristically the purest water in the hydrologic cycle, but even so it may collect from less than 1 to several hundred milligrams of dissolved material per litre of water during its fall through the atmosphere. At the earth's surface some of this water may infiltrate into the ground, and because of water's capacity for rock weathering and organic reactions in the presence of oxygen and carbon dioxide, as soil moisture it is characteristically more mineralized than the water of precipitation.

In the degradation process, overland runoff and flow in streams are the dominant factors in erosion and in transportation of sediment, floating materials, dissolved gases, and organisms. Ground water, on the other hand, generally is the prime gatherer of soluble minerals, and the solids it dissolves depend mostly upon the chemistry of the minerals contacted and the already present dissolved load. In both surface water and ground water the solutes of the degradation process correlate with amount of precipitation; that is, for the United States as a whole, Rainwater (1962, pls. 1, 2) showed that streams draining areas of perennial water surplus generally contain calcium magnesium bicarbonate waters with less than 340 mg/l dissolved solids. This "normal" condition occurs during periods of low flow, when much of the water in streams is base flow from ground-water reservoirs; therefore, an abundance of water is able to dilute the products of natural degradation, and people have long counted on—or at least hoped for—such dilution as a solution to their pollution of water.

Like the rest of the country, the California region has water of high quality in streams whose headwaters are in areas of perennial water surplus. Ground water is also of high quality and has low mineralization in those places that receive runoff from the areas of surplus. Tables 1 and 2 include columns giving the range of dissolved solids in the well water analyzed in each reservoir. In all but 14 of the 134 reservoirs, at least some wells obtain water that meets the U.S. Public Health Service recommended standard for drinking water of not exceeding 500 mg/l dissolved solids. These water resources of low mineral content are highly prized and have been developed for public supplies by the largest cities in the region (table 5). Throughout the area of perennial water surplus and in many of the valleys that receive those surpluses, ground water has generally less than 300 mg/l dissolved solids, chiefly calcium, magnesium, and bicarbonate (fig. 11).

Areas of perennial water deficiency characteristically have insufficient outflow to the ocean to carry all the solids that have been dissolved in the water, and extensive areas of this kind are in closed basins devoid of outflow. Increasing aridity is reflected in increasing mineralization of the ground water, and the closed basins in the desert may contain some highly saline ground water. In these basins the waters may be changed significantly by meteorological extremes: An exceptional storm may produce flood waters to be stored on the surface or underground, and this water may dissolve salts that had been precipitated or may dilute waters already accumulated, as shown by periodic analyses of waters from some wells in the Mojave River valley (State No. 6–40) (Miller, 1969).

Unfortunately, any water near the land surface may be lost by evapotranspiration, leaving dissolved minerals more concentrated in the water remaining or residual mineral evaporites. For example, in an area of perhaps 15,000 square miles (40,000 km^2) in southern California and Nevada, the water that moves toward the lowest part of Death Valley generally increases in salinity during this movement and exceeds 10 times seawater salinity near Badwater, the lowest point of a saltpan occupying 200 square miles (500 km^2); moreover, the changes in composition of the brines as they move into the saltpan are generally those expected from the solubilities of each salt in pure water (Hunt and Robinson, 1966). Some variations in composition are traceable to various source rocks, as for example the cottonball borates that were transported by 20-mule teams; these have been derived from such streams as the Owens River and the Mojave River, which carry small quantities of dissolved boron from mountain headwaters into the desert.

The South Lahontan and Colorado Desert subregions of eastern California have many closed basins with saltpans (pl. 1) smaller than Death Valley but similar to it in that they are underlain by salt and briny ground water; many are in the midst of extensive areas where the ground water occurs in similar saline and brackish zones (California Department of Water Resources, 1964c). Some zonation is also evident in the ground

TABLE 5.—*Megalopolitan water supplies*

[Adapted from Durfor and Becker (1964)]

Source	City	Population served (millions)	Chemical constituents, in milligrams per litre							
			SiO_2	HCO_3+CO_3	Ca+Mg	SO_4	Na+K	Cl	Hardness as $CaCO_3$	Dissolved solids
1	San Francisco	1.6	2	4	1	1	1	1	3	10
2	Oakland	1.0	10	22	9	0	3	5	23	40
3	Sacramento	.2	21	69	17	7	11	8	52	110
4	Los Angeles	1.4	31	123	29	23	35	16	81	212
5	Fresno	.15	68	118	26	6	21	6	82	221
6	Long Beach	.2	20	187	14	13	72	20	37	229
7	Orange County	.5	--	155–270	60–165	35–255	30–100	15–105	170–470	285–875
8	San Jose	.4	31	237	69	23	30	32	203	335
9	San Diego	.3	12	74	95	290	104	92	282	666

Sources and date of sample:
1. Hetch Hetchy Reservoir on Tuolumne River, 7/8/61.
2. Pardee Reservoir on Mokelumne River, 1/30/62.
3. Filter plant on Sacramento River, 7/26/61.
4. San Fernando Reservoir, Owens Valley aqueduct, 7/25/61.
5. Composite of 58 wells, San Joaquin Valley, 7/19/61.
6. Composite of 35 wells, Los Angeles coastal plain, 7/60–7/61 average.
7. Range in 130 wells, Orange coastal plain (California Department of Public Health, 1962), 1961–62.
8. Composite of 119 wells, Santa Clara Valley, 7/20/61.
9. Alvarado Treatment Plant, Inc., San Diego River and Colorado River, 1/24/62.

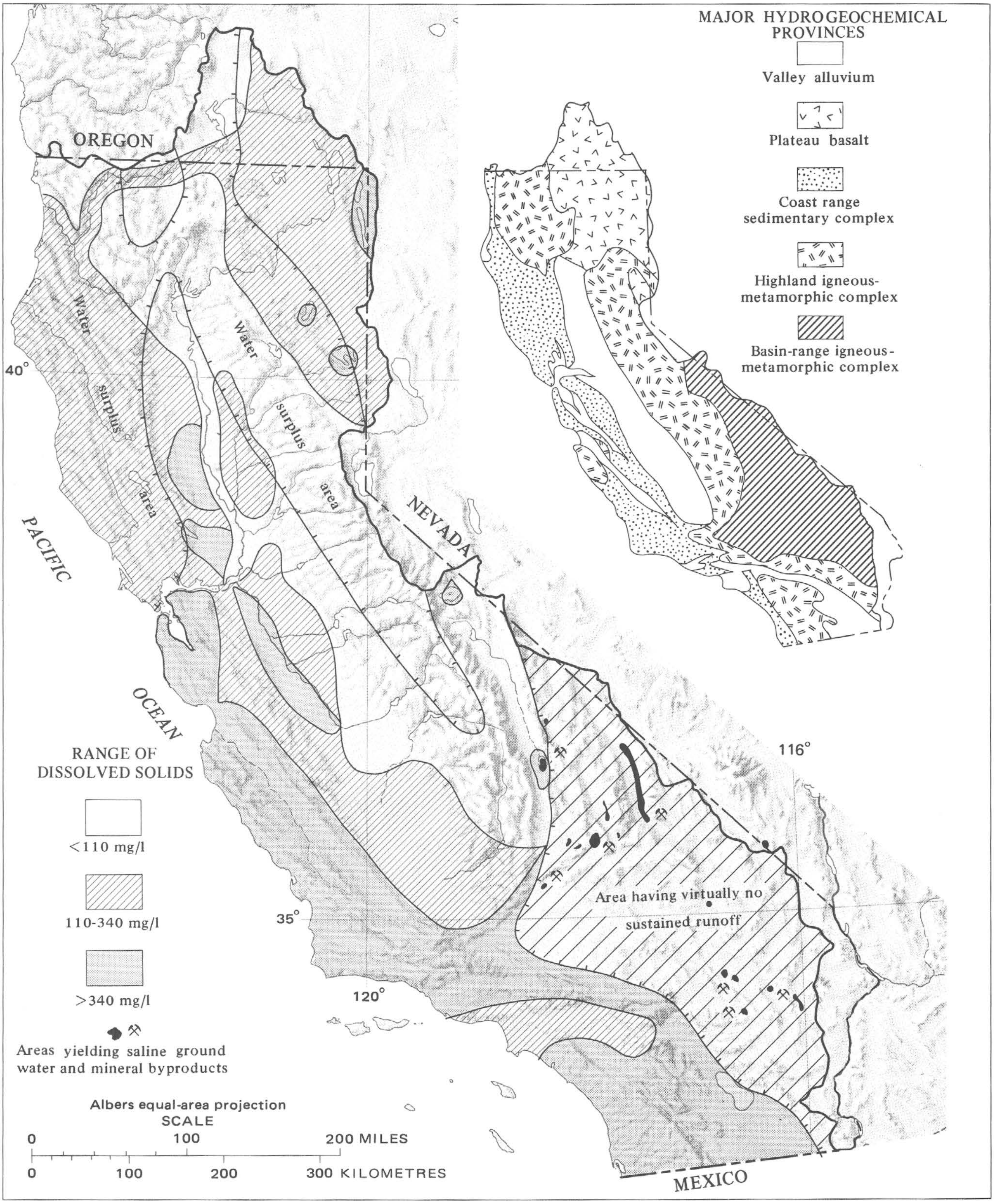


FIGURE 11.—Chemical characteristics of the base flow of streams

water in the closed Tulare Basin at the south end of the Central Valley, where water from the Sierra Nevada is a calcium bicarbonate type with less than 100 mg/l dissolved solids; sodium, sulfate, and chloride increase to the west and are dominant in the mineralized waters along the west slope. Although saltpans might be expected in the lowest areas, the Tulare and Buena Vista lake beds, outflow has evidently been sufficient to carry the more soluble salts over into the San Joaquin River, even during the past century; however, even though the river is throughflowing, sodium, chloride, and sulfate have accumulated in ground water in the western and lowest parts of San Joaquin Valley. A significant increase of chlorides also is found in the ground water along the lower western part of the Delta. A reconnaissance study of minor tributaries to the San Joaquin and Sacramento Rivers in the lower part of the valley (Richardson and Rantz, 1961) indicates that the alluvial materials are sufficiently permeable to permit significant interchange of surface water and ground water; consequently ground-water recharge may be at rates as great as 3 feet (1m) per day, and some seasons the streams gain comparable amounts from ground-water discharge. In this area of abundant evaporites and saline residues, this interchange of waters contributes to the deterioration of both.

In the four subregions along the Pacific Coast, outflow to the ocean from each drainage basin is likely to occur at some time during the winter rainy season; however, in summer most streams cease flowing for several weeks or months, and the larger streams generally contain only the base flow discharged from ground-water reservoirs, except where there are releases for fish or navigation, where irrigation water is stream transported, or where return flows augment stream flow. Significant concentrations of sulfate, sodium, and (or) chloride are characteristic of base flows of streams draining the areas of perennial water deficiency south of San Francisco Bay.

Several coastal streams have two or more ground-water reservoirs within their drainage basins, separated by impermeable rocks and canyons but connected by streams so that the discharge from one ground-water reservoir may become the recharge for another. Nowhere are chemical analyses found to document adequately either the natural hydrologic cycle or the pollution achieved by man, but the analyses may help in determining the relative contributions of streamflow, local precipitation, and artificial recharge to ground water in storage. Thus along the Napa River (table 6) the midvalley and downvalley ground waters, perhaps because of some recharge from precipitation, are more dilute than those near Calistoga, which are in marine sediments. In Salinas Valley also the dissolved solids in ground water decrease downvalley, where the precipitation is greater. But in several basins along the South Coast, where water deficiency is more pronounced and perennial, the ground water downstream has greater dissolved solids than in midstream well fields, which in turn are more mineralized than ground waters farther upstream.

In the Santa Ana River drainage basin, salinity of the confined and semiconfined ground water increases downstream to the Santa Ana Canyon. At the entrance to the canyon, ground water is forced to the surface by bedrock and becomes available for infiltration downstream. In 1954, the ground water underlying most of the inland sector of the coastal plain of Orange County, including the recharge area below Santa Ana Canyon, ranged from 400 to 600 mg/l dissolved solids. But in 1966, the dissolved-solids concentration in much of the basin was greater than 600 mg/l and exceeded 1,000 mg/l in the area of artificial recharge below Santa Ana Canyon (Moreland and Singer, 1969). The quality of ground water deteriorated because of artificial recharge by water imported from the Colorado River and by the base flow of the Santa Ana River.

AGRICULTURAL POLLUTION

As a natural effect of water in contact with rocks and soil, dissolved solids are commonplace in natural waters. However, when arid lands are irrigated with water from surface reservoirs created in the desert or with water imported from other river basins, these dissolved solids remain in the water, not consumed by

TABLE 6.—*Dissolved solids in ground water along coastal streams*

[Values in milligrams per litre; data from California Department of Water Resources, 1949, 1958b, 1964a, 1967b, 1970a]

Subregion	Upstream well field	Midstream well field	Downstream well field
San Francisco Bay:			
Napa River	Calistoga, 550–600	Rutherford, 200–250	Napa, 300–500.
Central Coastal:			
Salinas River	King City, 1,000–1,500	Gonzales, 1,000–1,300	Nashau, 500–700.
Santa Ynez River	Cachuma, 550–575	Buellton, 800	Lompoc, 1,500–2,000.
South Coastal:			
Santa Clara River	Piru, 700–900	Santa Paula, 800–1,000	Oxnard, 800–900.
Upper Santa Ana River	San Bernardino, 200–300	Riverside, 500–700	Corona, 850–1,000.
Lower Santa Ana River	Santa Ana Canyon, 1,000	Garden Grove, 650–700	Bolsa, 300–500.
San Luis Rey River	Pauma Valley, 300–350	Rancho SLR, 550–1,500	San Luis Rey, 1,500–3,000.

evaporation and transpiration, and thus increase the concentration of salts in the soil, in water percolating to a ground-water reservoir, and in surface-return flows. In this way both the quantity and quality of water resources are modified. Irrigation, even though it may simulate natural processes, tends to deteriorate the water, and thereby man causes pollution.

In irrigation—the dominant use of ground water in the California Region—the water used nonconsumptively may percolate downward to the water table or it may run off in ditches and stream channels. It may carry minerals dissolved from the soil zone as well as identical minerals dissolved by infiltrating rainfall or overland flow during the rainy season. In the Lompoc area of Santa Ynez Valley, Evenson (1965) estimated that since 1960 the withdrawal for irrigation and return by percolation may have doubled the concentration of chloride and sulfate ions in the shallow ground water. In this and other basins having seasonal outflow of water, artificial storage and the use of that water for irrigation can accelerate the natural degradation process, increasing the salinity of the shallow ground water or of the surface water in periods of low flow. Although human activities have doubtless contributed to the deterioration of shallow ground water in many places, how much manmade pollution has been added to natural contamination cannot generally be determined with certainty.

About one-twelfth of the natural runoff of the California Region comes from the San Joaquin River drainage basin, but the outflow is only half as great because of evapotranspiration. Degradation of ground water and surface water as they move through the valley is indicated by data summarized in table 7. As shown, the flow of the San Joaquin River below Friant Dam decreases by natural losses and diversions for irrigation and then is increased somewhat by return flows, both quantity of water and content of dissolved solids. The dissolved load continues to increase downstream, but the concentration is less because of dilution by tributary inflows. Although some of this degradation is natural, some results from the use of the water for irrigation, and the increases in recent years both in chlorides and in dissolved solids indicate increasing agricultural pollution by man. The ground water is of highest quality along the east slope and has the greatest content of dissolved solids in the lower part of the valley.

Beginning in June 1951, the Central Valley project has imported water from the Delta into lower San Joaquin Valley; in the first 7 full years of operation, the Delta-Mendota Canal carried 6.8 million acre-feet (8.3 km^3). In several places this imported water has diluted the surface water or the ground water in the lower San Joaquin Valley, but the ultimate effect of the increased supply for irrigation of these arid lands has been greater evapotranspiration and greater degradation of the ground water in the valley and of the surface-water outflow (fig. 12). The measured increases (table 7) of dissolved solids and chloride since 1951 may be evidence of pollution traceable to man's development and use of the water resources. Nevertheless, too little is known of the patterns and rates of flow of the water in the area to be certain.

TABLE 7.—*Degradation and pollution of water in San Joaquin Valley*

[Based on averages compiled from California Department of Water Resources (1960b, p. 116, 134–141); quantities in milligrams per litre]

A. Surface Water (San Joaquin River)

Locality	Chloride		Dissolved solids	
	1938–51	Increase by 1955–59	1938–51	Increase by 1955–59
Friant Dam	3		35	
Mendota (average flow decreases 75 percent; imported water enters river)	3	+60	45	+245
Fremont Ford (average flow increases 50 percent	120	+110	430	+260
Newman (average flow doubled by inflow of Merced River)	85	+85	355	+270
Grayson (average flow doubled by inflow of Tuolomne and Stanislaus Rivers)	100	+40	400	+120

B. Ground Water

Locality	Chloride prior to 1951	Dissolved solids	
		Prior to 1951	Change by 1955–59
Madera	40	280	None
Firebaugh	90	370	
Dos Palos	350	800	+200
Los Banos	100	500	
Gustine	55	530	+100
Los Banos Creek	425	1,270	
Turlock	40	300	None
Hills Ferry	380	1,000	−130
Patterson (shallow)	400	1,900	None
Patterson (deep)	90	1,000	None

Imports from the Colorado River to the California Region generally carry more than 800 mg/l dissolved solids, perhaps twice as much as the native water in most areas where the imported waters are used. Imperial Valley, the chief importer for irrigation, receives about a ton of salts in each acre-foot of water. To maintain a salt balance suitable for crops, it is necessary to irrigate with enough water to flush the salts from the soil through an intricate system of drains to eventual disposal in the Salton Sea. In Coachella Valley an underlying ground-water reservoir was the sole source of water for irrigation prior to 1948 and yielded about 100,000 acre-feet (125 million m^3) in 1937, chiefly from artesian wells southeast of the town of Indio where the valley is below sea level. Imports from the Colorado River began in 1948 and increased to more than 300,000 acre-feet (370 million m^3) after 1952, of which more than 20 percent soon reached the Salton Sea via surface drains (California Department of Water

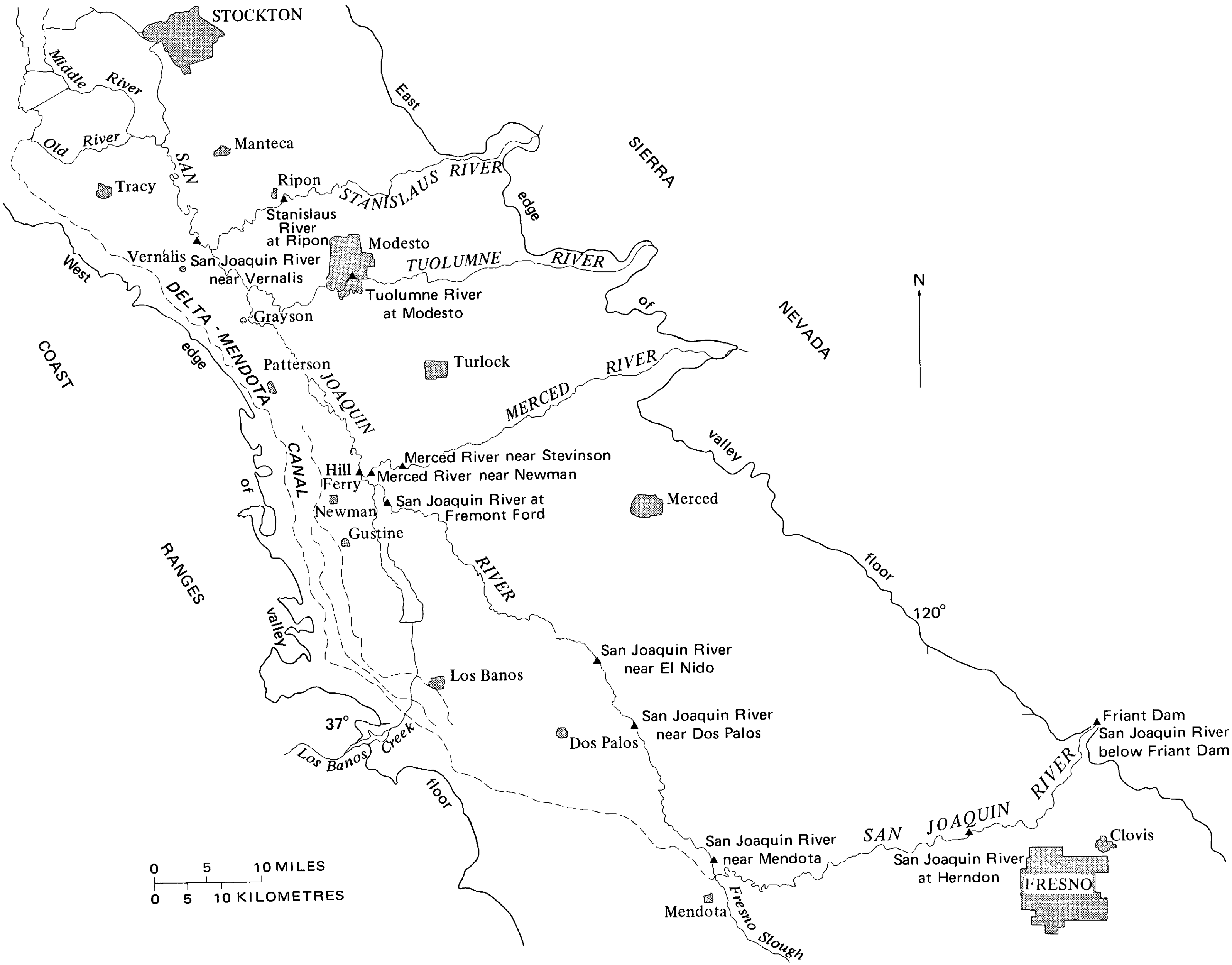


FIGURE 12.—Cities, towns, rivers, and gaging stations along the San Joaquin River.

Resources, 1964d). The progressive decline of water levels in artesian wells was slowed or halted as withdrawals from wells were reduced. Ground-water storage was increased by downward percolation of the imported water into a semiperched zone above the confined aquifer; however, with the mineralization of the Colorado River and the addition of the residual salts from irrigation and fertilizers, the shallow ground water now contains dissolved solids exceeding 3,000 mg/l and is unsuitable for domestic or agricultural use.

Agriculture has many byproducts and end products—at food packing and processing plants, feed lots, barnyards, and septic tanks—which may pollute water. Some are noxious, others foul smelling, but all are generally biodegradable, eventually being used in other living processes or reduced to their basic components of oxygen, nitrogen, water, and carbon dioxide. Notable exceptions are the persistent chemicals used as fertilizers, pesticides or herbicides, or cleaning agents, including some that are very soluble in water and others only slightly so. Presumably some of these chemicals applied over the land surface are dissolved in water that percolates downward and into ground-water reservoirs, and those used in households may similarly percolate from septic tanks. But quantitative data are meager and are limited to studies of small areas where people have been concerned about possible health hazards.

An example of an investigation of agricultural pollution is that concerning nitrates in ground water in the Tulare Basin of the Central Valley. Nitrate concentration exceeds U.S. Public Health Service drinking water standards in water from numerous wells in the irrigated areas of the Tulare Basin, especially from the Kaweah River southward to Bakersfield and beyond (California Department of Water Resources, 1970h). The town of Delano is in the midst of this area and is exceptional in the investigation and monitoring that has been undertaken to discriminate the agricultural pollution from the natural degradation of the water. As reported by the California Department of Water Resources (1968f), water from many wells near Delano have nitrates in excess of 45 mg/l. For half a century wells were the sole source of water for irrigation, and water levels were lowered as much as 250 feet (75 m) by 1950; however, since 1951, the Friant-Kern Canal has provided some of the water for irrigation, the rate of pumping has been reduced, and water levels have recovered as much as 165 feet (50 m). Fertilizers applied in the Delano area at annual rates as great as 1,000 pounds per acre (or kilograms per hectare) are suspect as a likely source for the nitrates, which are most concentrated in areas (1) that have been irrigated for the longest period of time and (2) under which ground water has risen markedly in recent years as surface water has been applied for irrigation. On the other hand, the nitrates may be of natural origin, at least in part, for analyses have indicated excessive concentrations of nitrate in several wells in 1945 and earlier years. Elsewhere in the Central Valley excessive nitrate concentrations are far less common, although the geologic and hydrologic conditions are similar. However, excessive nitrate has been reported in several ground-water reservoirs along the central coast (California Department of Water Resources, 1971d).

Public concern over the effects of pesticide use led to a study of the chlorinated hydrocarbon DDT, applied to a test plot of alkaline clay loam near Dos Palos in western San Joaquin Valley (California Department of Water Resources, 1968h). Although the land had never been cultivated prior to the test, the soil contained fairly high concentrations of DDT to depths of more than 6 feet (2 m), probably from nearby windblown aerial spray. The test plot was flooded three times for periods of 75–125 days each and at intervals of 9 months. Before the first two floodings only, DDT was applied at rates of 2–4 pounds per acre (or kilograms per hectare), slightly higher than normal for the area; with the third flooding rice was grown and harvested. The effluent from the first two floodings, both as surface runoff and in tile drains, contained considerably less than 1 part per billion of DDT, indicating its slight solubility and strong affinity for the soil, which retained most of it. The effluent after the third flooding, however, contained about 10 times as much DDT as that after the second flooding, an ominous indication of accumulation, stability, and long-term response of the toxic substance. The study was unfortunately not continued long enough for a full evaluation of the relative significance of leaching and of degradation by biological and chemical reactions. No comparable studies have been made in recharge areas of ground-water reservoirs to show the extent of entrainment of chlorinated hydrocarbons by downward percolating water.

URBAN POLLUTION

The problems of pollution of water in urban areas are not unlike some of the pollution problems in rural areas. Although a concentration of people produces a large volume of biodegradable wastes, they cannot be broken down within the space and time available on a city lot; also, the importation and use of mineral and chemical substances are likely to increase the volume and variety of dissolved materials in the water in urban areas, as do the chemicals spread over the land or utilized in households in rural areas.

In many rural areas of sufficient permeability, dug wells and septic tanks have been commonplace for domestic water supply and disposal, the septic tank holding the waste water until depleted of its organic materials by chemical reduction and then releasing it to the soil zone and perhaps to ground water. Although this is a usable recycling system, it requires cleaning and rehabilitation, becomes less satisfactory in suburban crowding, and thus is generally replaced by sewerage systems in urban regions. If the sewerage system is restricted to collecting pipes for raw sewage and does not include plants for primary and secondary treatment of the sewage, it is inferior to the septic tanks it replaces, for even though it may carry away the wastes of individual landowners, pollution abatement is nil. The organic wastes then may pollute streams and canals, soils, lakes and ponds, bays and estuaries, and the ocean but probably not ground water, because most living organisms cannot survive for long the anaerobic conditions as in a ground-water reservoir.

Standard sewage treatment is intended to remove most of the biodegradable components but not the dissolved inorganic solids. As a general average or rule of thumb (McGauhey, 1971), domestic use of water is likely to add about 300 mg/l to the original dissolved solids, and if the water is recycled, another 300 mg/l is added. This manmade increase in dissolved solids constitutes pollution of the resource that receives the sewage effluent, whether stream or lake or ground water. Studies in several areas (table 8) show sewage effluent, for the period of record, to have increased the maximum observed dissolved-solids load in ground-water reservoirs by 1,200 mg/l. In the study of San Bernardino (California Water Resources Control Board, 1965) undertaken when housewives everywhere were using the persistent foaming ABS (alkylbenzenesulfonate) detergent, water-quality factors were excellent tracers of ground-water movement.

In some urban areas where the shallow ground water is more mineralized than that at greater depth, the salinity distribution may have resulted from natural processes of degradation, expecially in areas of perennial deficiency where salt residues from evaporation are redissolved by storm waters as they infiltrate into the ground or in areas where irrigation could have caused leaching and downward migration of dissolved minerals. In Ventura County (Basin No. 4–4 on pl. 1) and coastal Los Angeles County (No. 4–11), the quality of water in shallow aquifers is generally inferior to that at greater depth (California Department of Water Resources 1965b, 1968c; California Department of Public Health, 1968). The relative importance of pollution and natural degradation was not determined, but strict water-well standards were recommended to prevent influx of inferior water to the deeper aquifers.

Garbage, rubbish, and other solid wastes (known collectively as refuse) are potential pollutants of the water if they are soluble. Most refuse disposal in the California Region is in sanitary landfills operated by cities, towns, and counties. Many of these are in areas overlying ground-water reservoirs, and the pollution of ground water by decomposition products is a hazard. The effects of solid-waste disposal upon the quality of ground water in several localities in southern California are summarized in table 8 from studies by the

TABLE 8.—*Ground-water reservoir pollution by municipal wastes*

[Data for sewage treatment plants from California Department of Water Resources, 1965c, 1968g; California Water Resources Control Board, 1961, 1965; Miller, 1969. Data for sanitary landfills from California Department of Water Resources, 1969b]

State No. (pl. 1)	Valley	Year	City	Pollutants	Maximum observed increase (mg/l)	Maximum observed extent	
						mi	km
				Sewage-treatment plants			
4–11	Coastal plain	1945	Alhambra	Phenols	+0.1	6	10
6–40	Lower Mojave	1960	Barstow	Phenols	+1.1	4	6
4–14	Upper Santa Ana	1963	San Bernardino	Alkylbenzenesulfonate	+2.5	10	16
5–22	San Joaquin	1963	Fresno	Dissolved solids	+400	2	3
				NO_3	+30		
				Alkylbenzenesulfonate	+.3	.1	.2
3–15	Santa Ynez	1966	Lompoc	Dissolved solids	+200	2	2
				Cl	+50		
				Sanitary landfills			
4–14	Upper Santa Ana	1952–54	Riverside	Dissolved solids	+500	0.6	1
				Cl	+190		
4–13	San Gabriel	1958–61	Monrovia	CO_2	+1,200	.3	.5
4–13	San Gabriel	1962–65	Azusa	Dissolved solids	+160	.3	.5
				CO_2	+120		
				NO_3	+15		
4–12	San Fernando	1962–65	Glendale (Scholl Canyon)	Dissolved solids	+1,200	0	0
				Fe	+250		
				Mn	+1,200		
				Zn	+1,000		

California Department of Water Resources (1969b).

INDUSTRIAL POLLUTION

Most industries depend upon municipal systems for their water supply and disposal, and about half the volume of sewage treated in municipal facilities comes from industrial sources. The pollutants from numerous industries, for example, food processing, are mostly biodegradable, but other pollutants, such as those included in table 8 are troublesome to incorrigible in these treatment processes.

Many large industrial plants have developed their own water-supply and disposal facilities, which may include treatment before use and before return of the used water to public resources. The principal industrial use of water in the California Region is for cooling, especially for thermal-electric power generation which uses more than 12 million acre-feet (15 km^3) annually, 90 percent of which is brackish or saline (Murray, 1968, p. 30). In self-supplied manufacturing, industries reportedly have used about 917,000 acre-feet (1.1 km^3) of freshwater annually (California Department of Water Resources, 1964e), but in 1965 the estimated total (Murray, 1968) was only 530 mgd (0.75 km^3). These figures on industrial use are very tentative, but even less is known about industrial water pollution, for the subject has received little attention from industry and is of apparently little interest to the general public.

The California Department of Water Resources survey of industrial uses in 1957–59 showed that the principal uses of freshwater in manufacturing were approximately 25 percent for food and drink processing, 22 percent for lumber and wood products, 16 percent for petroleum refining, 10 percent for chemical products, 8 percent for metals and machinery, and about 8 percent for paper products. One-third of the manufacturing use of water was in southern California, and almost as much in the San Francisco Bay area.

Examples of industrial waste pollution of ground water are common but generally lack the quantitative data essential to evaluate the pollution. Three examples of pollution by disposal of water-softener regeneration brines have been reported (California Water Resources Control Board, 1961) and are summarized in table 9.

Solid wastes in the California Region amount to about 4½ pounds (2 kilograms) of refuse daily per capita, of which 15 percent is garbage, 30 percent paper and cartons, and 10 percent glass and metal containers. This personal refuse, however, is only about 10 percent of the total solid wastes of an industrial civilization, and most of these solid wastes are disposed of on lands owned or leased by the individual companies. Such landfill may make land of natural lakes, bays, and streambeds; plains or smooth slopes in rough country; or relief on level lands. But by modifying the land surface, these landfills also modify the hydrologic cycle in the locality, and soluble material may be dissolved and pollute ground water or surface water.

MINERAL-RESOURCE DEVELOPMENT

The development and use of the land is primarily concerned with resources other than water, including the soils for agriculture, fossil fuels, metallic and other minerals for manufacturing, rocks and sediments for construction, and the land surface for occupancy. In such development water becomes a byproduct that may be of some benefit or may be detrimental (Thomas, 1969). Water may constitute a nuisance if it harms the development and use of the earth's resources and invades recognized property rights. Conversely, the development and use of the land resources may have

TABLE 9.—*Ground-water reservoir pollution by industrial byproducts*

[Data from California Department of Water Resources, 1955a, 1968g; California Water Resources Control Board, 1961; Piper and Garrett (1955); Williams and Wilder (1971)]

State No.	Valley	Locality	Year	Pollutants	Maximum observed increase (mg/l)	Maximum observed extent mi	km	Remarks
4–4	Oxnard–Santa Clara.	Saugus	1942–49	Water softener regeneration brine.	Dissolved solids +5,000	0.4	0.6	Quality "normal" by 1953.
5–22	San Joaquin	Fresno	1953	do	do +1,400	.1	.2	
					Cl +750			
					Na +400			
3–15	Santa Ynez	Lompoc	1952	do	Dissolved solids +400	1	1.6	
4–11	Coastal plain	Dominguez Gap.	1928–48	Oil-field brine	do +3,200	1	1.6	
					Cl +1,700			
					Na +600			
4–11	Coastal plain	Norwalk	1953	do	Dissolved solids	1	1.6	
					Cl			
					Na			
5–22	San Joaquin	Raisin City.	1948–53	do	Dissolved solids +40	1	1.6	
					Cl +15			
			1954–55	do	Cl +2,600	.1	.2	Increase in same well in 7 months.
4–12	San Fernando	Glendale (Forest Lawn).	1968–71	Gasoline (broken pipe).		.3	.5	190 m^3 free gasoline removed; remanent taste and odor.

effects on water that interfere with the rights of others or that result in a nuisance.[5]

Ground water occurs with several minerals and fuels of economic value and may be useful in the development or processing of the resources, although it must eventually be disposed of somewhere. Some of these waters are of a quality suitable for other water users, but many are so mineralized that they would pollute the water in streams or ground-water reservoirs.

PETROLEUM

In California during 1959 (Musser, 1959, tables 1, 5, 6, 7), about 39,000 wells yielded 310 million barrels (50 million m^3) of crude petroleum, along with 800 million barrels of water generally saline enough to be classed as brine. About one-third of this brine was returned underground through 465 wells, either for water-flooding in the producing zone or for disposal. Sixty-nine thousand acre-feet (85 million m^3) of brine was left to be dumped into seepage ponds, stream channels or dry valleys, or other convenient location. In some places these least-cost methods of disposal had continued for decades, but in others they soon became unacceptable to water users and were discontinued. In many localities the ground-water reservoirs have been polluted by oil-field brines, and quantitative data are available for some, as summarized in table 9. The brines for surface disposal in San Joaquin Valley alone had aggregated 55,000 acre-feet (69 million m^3) in 1959; in several oilfields, the native ground water ranges from mediocre to unfit for use (California Department of Water Resources, 1956), but other oilfields, of which the Raisin City field is an example (California Department of Water Resources, 1955a), have been developed by going through the ground-water reservoir.

By 1972 most of California's oil-field brines were being recycled, increasing the yield of petroleum and reducing the pollution of ground-water reservoirs (California Division of Oil and Gas, 1972, tables 1, 5, 6, 7). In that year 39,600 wells produced 325 million barrels (52 million m^3) of oil and 1,700 million barrels (280 million m^3) of brine, but 95 percent of that brine was returned underground, 1,300 million barrels (210 million m^3) was injected through 11,800 wells for water flooding or as steam and hot water for secondary oil recovery, and an additional 340 million barrels (54 million m^3) was returned in 270 disposal wells. That left only 60 million barrels or 8,000 acre-feet (10 million m^3) of brine as a potential pollutant to freshwater resources.

EVAPORITES AND BRINES

Several desert basins east of the Sierra Nevada and the high mountains farther south (fig. 11) contain saline deposits of economic value, including common salt (sodium chloride), trona (hydrous sodium carbonate), salt cake or Glaubers salt (sodium sulfate), potash (potassium carbonate), borax (sodium borate), and bromide and lithium salts. These highly soluble salts were dissolved perhaps in a dominantly volcanic terrane by water at times and places of surplus and brought by water into an area of perennial water deficiency, where by natural processes of degradation the water became increasingly unfit for use and eventually disappeared. Some of the oldest deposits are the borax beds at Boron, accumulated in Miocene lakes 20 million years ago, dried and kept dry in subsequent time. In the present drainage systems, the degradation process is continuing today. The most favorable time for accumulation in these desert basins, however, was during the pluvial-glacial stages of the Pleistocene Epoch, when water was sufficiently abundant to form numerous large and deep lakes in which long-continued evaporation left saline deposits that extended to considerable depth in some basins.

Every basin of interior drainage is likely to have a playa in its lowest part where floodwater can accumulate with its clastics and then evaporate or where ground water is shallow enough to evaporate and leave soluble salts. Economic value of these salts has depended partly upon the degree to which they have been separated from clastics and from each other. Four playas within a hundred kilometres of the Colorado River have extensive crystal bodies that are practically free of clastics (Ver Planck, 1958). At Danby Lake in Ward Valley (State No. 7–3), nearly pure halite was quarried from 1890 intermittently until 1942. Rock salt was produced at Bristol Lake in Bristol Valley (No. 7–8) beginning in 1909; however, the brine there also has calcium chloride which is readily separated from the common salt by solar evaporation, and this has been the sole product since 1931. Cadiz Lake (No. 7–7) 22 miles (35 km) to the southeast has a similar sodium chloride–calcium chloride brine, but none has been produced. On the other hand, Dale Lake (No. 7–9) 25 miles (40 km) south of Bristol Lake has abundant sodium sulfate with the chloride and is readily separated at low temperature while the common salt

[5]As broadly defined by the California Water Code (sec. 13050), a nuisance is "anything which (1) is injurious to health or is indecent or offensive to the senses, or an obstruction to the free use of property, so as to interfere with the comfortable enjoyment of life or property, and (2) affects at the same time an entire community or neighborhood or any considerable number of persons, although the extent of the annoyance or damage inflicted upon individuals may be unequal, and (3) occurs during or as a result of the treatment or disposal of wastes." The nuisance factor of water is not within the scope of this appraisal of water resources.

remains in solution; both commodities were produced in the 10 years ending in 1948.

Several other playas have histories of commercial production of common salt. In Saline Valley (No. 6–17) freshwater was used to dissolve the rock salt, which then was recrystallized in place, but production ceased after 1930, victim of transportation costs and the Depression. Generally the desert producers of salt have lost out to the producers of salt by evaporation of seawater close to cities. One survivor in the desert has been at Koehn Lake in Fremont Valley (No. 6–46), nearest to the Los Angeles area, where salt is recovered from inflowing floodwaters that become brine and then salt residue by solar evaporation; also, brine comes from wells as much as 100 feet (30 m) deep. Within 1 mile (1½ km) southwest of the playa, however, the ground water from flowing wells is fresh enough to be used for irrigation (California Department of Water Resources, 1969a).

In Searles Valley (No. 6–52) the degradation of ground water has proceeded to the ultimate in concentration, variety, and economic value of dissolved solids (U.S. Geological Survey, 1966, p. 104, 111, 385–391). This playa too has a crystal body free of clastics extending over 7,500 acres (30 km^2), with nearly pure rock salt to a depth of 10–15 feet (3–5 m). Beneath the halite is a zone of crystalline salts averaging 60 feet (20 m) thick, impermeable clay less than 15 feet (5 m) thick, and a deeper saline zone 30 feet (10 m) thick, all extending over an area exceeding 25,000 acres (100 km^2). Brines saturate both saline zones and account for about 40 percent of their total volume, and the brines in both zones are pumped selectively from wells for commercial production. The brines are distinctive in that they are complex alkaline waters with 350 parts dissolved solids per thousand of water, of which about 20 percent is Na_2SO_4, 14 percent Na_2CO_3, 14 percent KCl, 5 percent borax, some commercial bromide and lithium salts, and more than 45 percent common salt that is unwanted and sluiced back to the playa. These percentages vary from well to well, from deep well to shallow well, and from time to time in the same well, and so production can be modified somewhat to fit market demand. Before processing, the brine may be enriched by solar evaporation, which preferentially crystallizes NaCl and adds to the halite crust.

The Searles Lake playa is the nearly dessicated remnant of a Pleistocene lake which was part of the Owens River drainage system and which accumulated the dissolved salts from a large area of the Sierra Nevada. Owens Lake has not overflowed for thousands of years and would need to rise 250 feet (75 m) to overflow, but ancient shorelines show that it has done so; the escaping water formed a lake in Searles Valley for extended periods, and that lake occasionally rose high enough to overflow into Panamint Valley (State No. 6–58). The dissolved solids that accumulated in Searles Valley as the water evaporated are a nonrenewable resource, at least until the next pluvial-glacial age.

The ground water in the crystal body, however, appears to be replenishable and sufficient to have sustained the industrial development of the past 45 years, even though the normal annual rainfall at Trona is only 4 inches (100 mm) ranging from 0.4 inch (10 mm) in 1953 to 9 inches (230 mm) in 1941. The brine that is pumped from wells goes through various evaporators and heaters and coolers as it is divested of its desirable salines; some water returns to the playa, but some is lost in the processing. Beyond the crystal body in the valley alluvium, brackish water is pumped at Valley Wells for washing and processing, and this pumpage has created a cone of depression that draws more mineralized water toward those wells as groundwater storage is depleted. No water suitable for domestic use has been found in the valley, and the residents depend upon water imported via pipeline from Indian Wells Valley (No. 6–54).

In Owens Valley (No. 6–12) human activities have increased the degradation of the water and accumulation of salines. Today the brines of the Owens Lake playa contain 31 percent dissolved solids (10 times seawater salinity), with a higher concentration of Na_2CO_3 (the only substance in commercial production) and a lower concentration of KCl and borax than the Searles brine. A century ago, Owens Lake had an area of 72,000 acres (300 km^2) and a volume of 2.4 million acre-feet (3 km^3). By 1913 it had dwindled to one-fourth of that volume because of increasing diversions from Owens River for irrigation. In subsequent years, when practically the entire riverflow was diverted for the Los Angeles municipal supply, the lake became an artificial playa.

SAND AND GRAVEL

In contrast to the water-deficient environment that is essential for the preservation of evaporites, sand and gravel are deposited in environments of water surplus, notably along the channels of major streams and especially those issuing from mountains (U.S. Geological Survey, 1966, p. 361–68; California Division of Mines and Geology, 1961, 1964, 1968). Many water-laid deposits of sand and gravel, now in arid or semarid areas, accumulated under conditions of greater volumes of water than now present, whether in ancient rivers or melting glaciers, in deltas, lakes, or bays; or in littoral currents. Many others are along the channels and in the valleys of the present stream systems and are closely related to them (fig. 13).

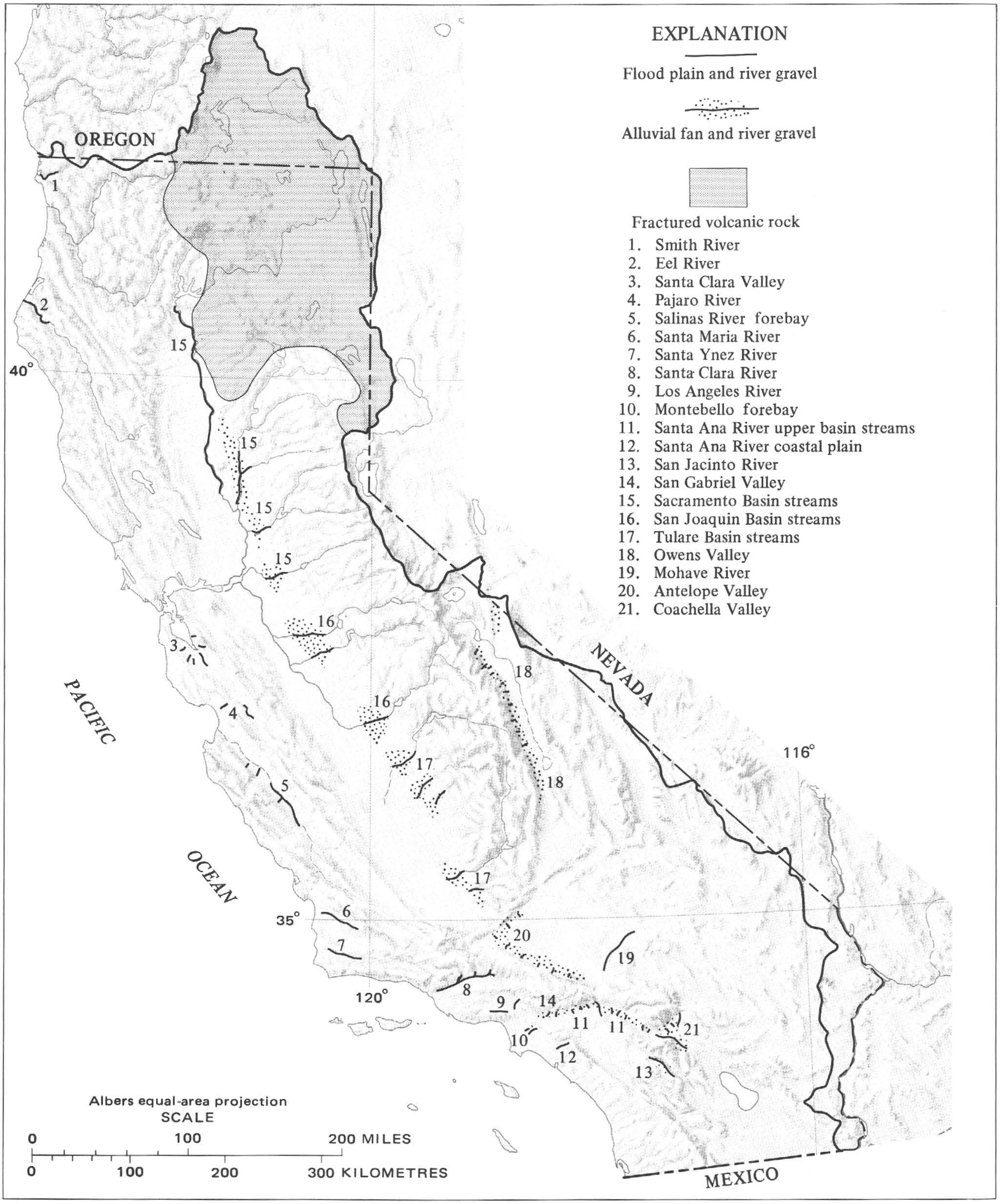


FIGURE 13—Outcrops of sand and gravel and other permeable rocks

Much of the sand and gravel at the land surface and therefore most accessible for use is also in areas where underlying ground water is naturally or can be artifically replenished, and in several urban areas gravel pits have become excellent sites for artificial recharge. In the construction of off-channel spreading basins for artificial recharge (see section "Recharge in Urban Areas"), the Orange County Water District obtains revenue from sand and gravel excavators, which materially reduces the cost of the basin construction. In the Central Valley many of the principal sand-and-gravel producing areas are in the zones of ground-water recharge along such streams as the Sacramento, San Joaquin, Kings, and Kern Rivers. (See section "Recharge in Central Valley.")

GEOTHERMAL ENERGY

In several parts of the California Region, the circulation of ground water and steam has produced reservoirs of stored heat at depths shallow enough for economic recovery by means of wells. Currently the only production of geothermal energy is from "dry" steam at The Geysers (Koenig, 1969), in the northern Coast Ranges about 12 miles (20 km) southwest of Clear Lake (fig. 14), where in 40 wells 1,600–8,100 feet (500–2,500 m) deep the cool shallow ground water is sealed off. Condensing turbines are used for generation of electric power from the steam, and estimates of the field potential are as much as 1,000 megawatts, of which 180 is presently developed. The condensate water carries ammonia and boron in solution above permissible levels and is therefore discharged into disposal wells.

In other parts of the California Region, the geothermal resource consists of hot water underground. In the South Lahontan subregion in the headwaters of Owens River, Casa Diablo is an extensive area where temperatures as high as 180°C have been measured in wells and where hot springs discharging water averaging 11 mg/l boron have been an important source of the saline deposits of Searles Lake. In the Colorado Desert subregion an even larger geothermal resource underlies the Salton Sea and the Imperial and Mexicali Valleys to the south (Rex, 1971). Because some of the brine in the Colorado Desert area is very concentrated, surface disposal would cause unacceptable pollution of the Salton Sea; as suggested by Rex, some of the heat might be used for desalination of some of the brine, although numerous obstacles to such development are recognized.

OPPORTUNITIES FOR UTILIZING GROUND-WATER RESERVOIRS IN OVERALL WATER MANAGEMENT

As stated by the Committee on Water (1966, p. 48–49),

> A review of current efforts to manage water to serve the needs and desires of man reveals that all aspects of water management would be improved by planning that would maintain flexibility for the future, foreclose as few choices as practicable, and put fresh demands on science to predict consequences and to provide alternatives to meet changing needs***. The essential facts now are becoming well known, and the basic hydrologic problems have been defined. Still lacking is a broad recognition by scientists and engineers as well as policy makers that advances in the knowledge of water and its possible uses not only have changed the character of water problems, but have made it possible to deal with these problems in a greater variety of ways and more effectively than in the past.

Ground water has long been the alternative to surface water as a natural source of supply, especially valuable to the nonriparian landowner who is denied the use of surface water by the riparian doctrine. Large-scale development of ground water in the California Region began nearly a century ago, and wells now supply about 40 percent of the total need for freshwater. Many ground-water reservoirs, however, have a history of exploitation, overdevelopment, and depletion; others have not yielded supplies of satisfactory quality or quantity, or they do not look promising and have not been explored. It is, therefore, to be expected that some people would mark ground water as the alternative least likely to succeed and dismiss it by stating that "in the California region ground water has generally been developed to its maximum" (California Region Framework Study Committee, 1971, p. 48).

In comprehensive planning that considers a range of alternatives to meet changing needs, ground-water reservoirs may have an accessory but nevertheless essential role. Desalination of seawater will require surface or subsurface water-storage facilities whenever and wherever the demand is less than the production of desalted water; for inland areas where the cost of pipelines to the ocean would be prohibitive, desalination requires saline or brackish water as raw material and feasible disposal of residual brines, and these requirements demand saline ground-water reservoirs for both supply and disposal. Reclamation of nonconsumptively used "waste" water will also generally require storage facilities for the water so reclaimed until the time comes to use it again. Weather modification may lead to significant increases in precipitation but not from the cloudless skies that prevail during droughts when water is needed most; thus it will not be an alternative to the use of surface or underground reservoirs but must rely on them as tools for management of the augmented water resources. Watershed management, whether it uses impermeable surfaces to increase runoff or other techniques to increase infiltration, will doubtless depend on surface or underground storage of the water so yielded. Furthermore, the evapotranspiration that is labeled "nonbeneficial consumptive use" may be reduced by various means, one of which is management of storage in underlying ground-water reservoirs.

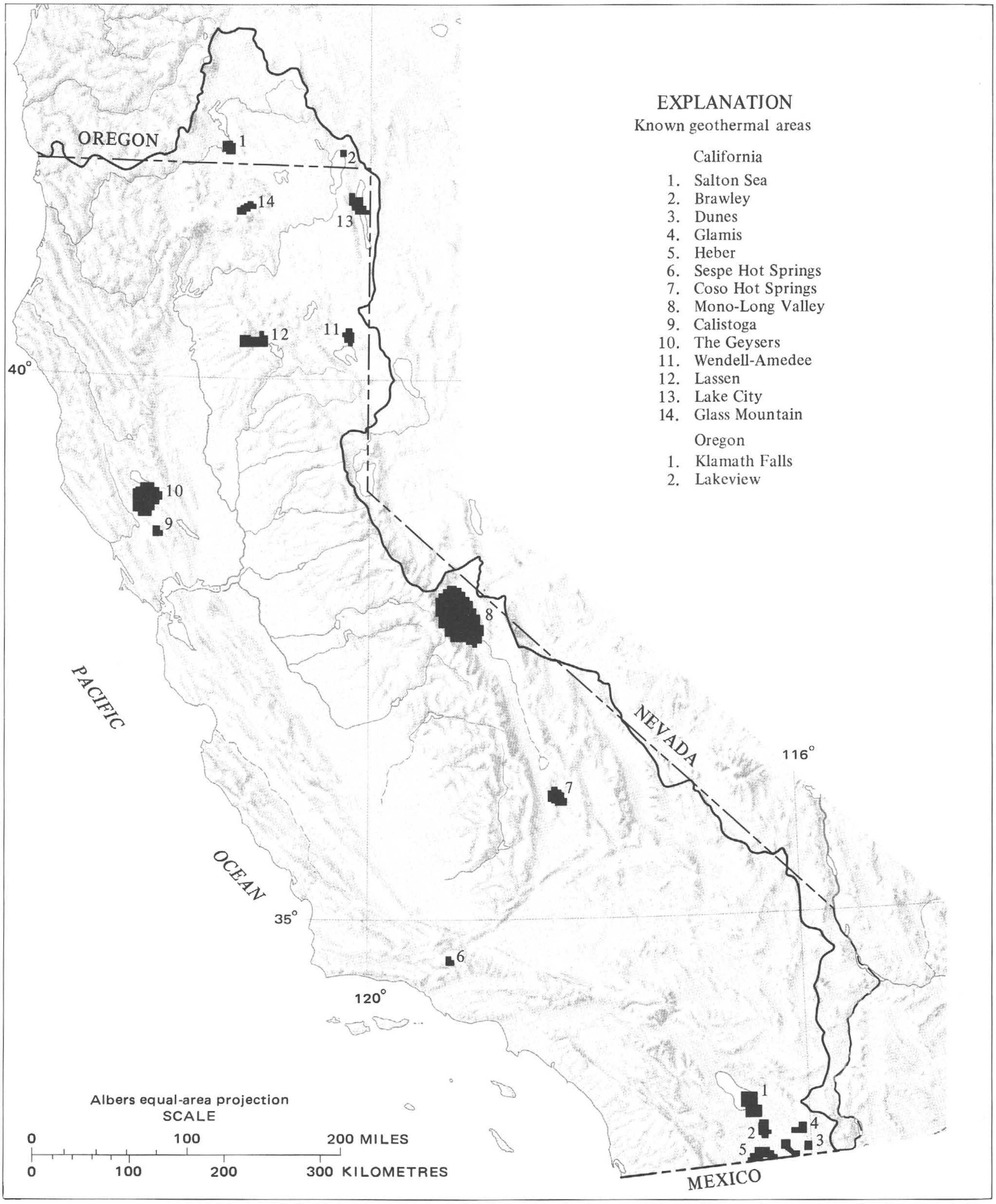


FIGURE 14.—Known geothermal areas in the California Region.

Each of these alternatives has the prime purpose of increasing the supply of usable freshwater; each requires expenditures in energy, manhours, equipment, and therefore money. If the water produced were stored in surface reservoirs for future use, substantial volumes must be lost by evaporation all year round in water-deficient areas (fig. 3) and throughout the California Region during the largely rainless summers. Ground-water reservoirs may become the preferred alternative, because the losses from them by evapotranspiration are characteristically far less. Also, ground-water reservoirs can be maintained and used in urban areas without denying or degrading the surface for other uses and without danger of disruption, spilling, or flooding disaster during earthquakes.

Artificial recharge is a prerequisite for effective management of underground space. Without it any replenishment of ground-water supplies is dependent upon the vagaries of nature, except for inadvertent human contributions from overirrigation or disposal of nonconsumptively used and polluted waters. Unless we have the capability of storing surpluses of water underground when they are available for use when needed, the use of ground-water reservoirs cannot exceed the limits set by nature (Committee on Ground Water, 1961, p. 92).

Where ground-water reservoirs can be operated as warehouses for accepting, holding, and releasing water as required, ground-water management becomes one aspect of integrated water management, involving conjunctive use of all water resources. Aside from warehousing of water in subsurface space, efficient water management requires the maintenance of the water with minimum deterioration. This depends upon the successful solution of problems in a variety of categories under the subject of "reservoir pollution." (See sections under "Reservoir Pollution.") Here the duties of management are likely to include monitoring, licensing, prohibiting, and punishing offenders.

ARTIFICIAL RECHARGE

Artificial recharge is the process of intentionally replenishing ground water through works provided for that purpose (Committee on Ground Water, 1961, p. 72). Ground water is replenished in many places by irrigation in exceedingly permeable soils, in natural recharge areas where the irrigator knows he will add to ground-water storage, and in some places by flooding to leach soluble salts from saline or alkaline soils; but these do not qualify as artificial recharge, nor do the various means of disposal of nonconsumptively used water as in septic tanks, pits and sumps, and seepage ponds.

As early as 1895 floodwaters were spread over the alluvial fan at the mouth of San Antonio Canyon to sustain the many flowing wells in the Upper Santa Ana Valley (No. 4–14) in southern California. The practice spread to other parts of the valley and was so successful that downstream users obtained an injunction to prohibit artificial recharge from local waters until adjudication of the waters of the river basin had been completed (Orange County Water District v. Chino Basin Municipal Water District). The Upper Santa Ana Valley provides excellent opportunities for artificial recharge (Moreland, 1972)— 7,500 acres (3,000 hectares) of unlined channels plus 60 off-channel basins aggregating 2,600 acres (1,050 hectares) with a recharge capability exceeding 3,200 cubic feet per second (90 m^3/s). The beds of major streams could absorb the water of a 5-year flood (peak 5–20 times the mean flow), and most streambeds could absorb waters of a 10-year flood (peak 10–100 times the mean flow).

As of 1958 (Richter and Chun, 1961), 54 agencies were practicing artificial recharge in California, chiefly in the South Coastal, San Francisco Bay, and Tulare Basin subregions. About 65 percent of the projects were basins or pits, and these received about 60 percent of the artificially recharged water; 23 percent used natural channels or artificial ditches or furrows, which accounted for nearly 40 percent of the total artificial recharge. Twelve projects used recharge wells, accounting for only 1 percent of the water applied. Artificial recharge totaled about 630,000 acre-feet (780 million m^3) in 1958, of which more than one-fourth came from the Colorado River. In 1962 and again in 1963, after a year when rainfall at Los Angeles was less than 5 inches (125 mm) and the least in a century, about 360,000 acre-feet (440 million m^3) of Colorado River water was used for artificial recharge. The Los Angeles County Flood Control District for nearly 40 years has used various types of water to replenish ground-water reservoirs in the South Coastal subregion and has probably more experience and more complete records on artificial recharge than any other single agency (Bianchi and Muckel, 1970).

RECHARGE IN URBAN AREAS

The artificial recharge reported for 1970 (California Department of Water Resources, 1971a) and summarized in table 10 was chiefly in the South Coastal and San Francisco Bay subregions, in four of the six most populous counties in California. In the San Francisco Bay area, most of the artificial recharge was by water of local origin—storm runoff delayed along natural channels or diverted into recharge basins—but 40 percent came from the Central Valley via the South Bay aqueduct. In the Los Angeles metropolitan area, most of the artificial recharge was by water from the Colorado River, but this amounted to only about 15 percent of the total Colorado import in 1970.

All the metropolitan areas of the California Region

TABLE 10.—*Artificial recharge reported for 1970*

Subregion	Source	Quantity (million m³)
San Francisco Bay	Local	107
	Imported	57
		164
Central Coastal	Local	33
South Coastal	Local	217
	Imported	[1]229
	Reclaimed	21
		[1]467
Tulare Basin	Channels	258
	Spreading basins	132
	Replenishing irrigation	43
		433
San Joaquin Basin	Channels	411
	Spreading basins	55
	Replenishing irrigation	471
		937
Total		2,030

[1]Includes 35 thousand acre-feet (43 million m³) of water from Colorado River injected into 120 recharge wells along saltwater barriers.

are in valleys and lowlands containing permeable alluvial fans, channels, and soils that are excellent for ground-water recharge. Storage of water in a metropolitan area has always been essential for distribution to people when they need it, but artificial surface-water storage in the metropolitan areas is costly because of exorbitant land values. Ground-water reservoirs have helped solve this problem. The urban areas thus have both the capabilities and incentives for artificial recharge of underlying ground-water reservoirs. They may, however, reduce or prevent natural recharge of underlying ground-water reservoirs because of impermeable roofs, streets, and pavements and the gutters, drains, and storm sewers that take rainwater away.

In southern California divergent achievements are shown on the coastal plain in Orange and Los Angeles counties. The principal area of artificial recharge by the Orange County Water District is along the Santa Ana River in the forebay area[6] below Santa Ana Canyon (fig. 7). Similarly the Montebello forebay, along San Gabriel River and Rio Hondo below the Whittier Narrows, is a major area of artificial recharge by the Los Angeles County Flood Control District. Farther west, the Los Angeles River also has a forebay which once served as a natural recharge area for ground water of the coastal plain; however, the urban sprawl of downtown Los Angeles into this area has made the dispatch of floodwaters the first priority. The channel has been paved with concrete, and the recharge to the Los Angeles forebay has been drastically reduced.

[6]In his Salinas Basin investigation (California Department of Water Resources, 1946), Russel Simpson divided the valley floor into five areas for analytical purposes, of which one was designated the "forebay" area—an area of coarse-textured alluvial soils and underlying materials in which ground water is unconfined; its ground water comes chiefly from the Salinas River and from ground water in the upper valley area, and it moves northwestward into confined aquifers in the pressure area, the principal area of pumping for irrigation. The term "forebay" has been accepted in California as appropriate for similar areas along several other streams where ground water is in permeable alluvium, unconfined and readily recharged from the stream, but then moves into confining conditions.

RECHARGE IN CENTRAL VALLEY

The annual pumpage from wells in the urbanized South Coastal and San Francisco Bay subregions is only about 10 percent of the total ground-water withdrawal in the California Region. By contrast, the Central Valley accounts for about 80 percent of the regional pumpage, predominantly in the San Joaquin Valley and the closed Tulare Basin, and in addition is estimated (California Division of Water Resources, 1970c, p. 69) to have received more natural recharge than the total recharge to all other ground-water reservoirs in the California Region. The form of the water table and other potentiometric surfaces of the ground-water reservoir indicates that recharge occurs chiefly along the east slope of the valley and especially from streams draining the Sierra Nevada. Several of these streams flow in channels and over alluvial fans with excellent recharge areas of permeable sand and gravel. (See fig. 13).

The Tulare Basin is especially well suited for artificial recharge by spreading, for the Kern, Tule, and Kaweah Rivers have shallow natural channels readily available for disposal of surplus water. Since 1938, the North Kern Water Storage District has spread surplus water when available for artificial recharge; it reported spreading 250,000 acre-feet (0.3 km³) in the 3 years 1956–58, when a million acre-feet (1.3 km³) was released to Kern River from Isabella Reservoir. The Kaweah Delta Water Conservation District and the Lower Tule River Irrigation District have also used surplus waters for artificial recharge in natural channels.

The streams that enter San Joaquin Valley north of the Kaweah River flow in trenches incised in the alluvial fans and plains of the valley. Some channels are in materials so impermeable that surface reservoirs are maintained on them with negligible loss by seepage; some flow over thin beds of sand and gravel which absorb so little water as to be negligible in recharge. To deliver water from these streams to the valley lands for irrigation has required major detention and conveyance works, but many of the irrigated lands and the stream channels and canals in the vicinity are excellent for artificial recharge of the underlying ground-water reservoir. Several agencies have used the channels of Ash and Berenda Sloughs and Chowchilla and Fresno Rivers for artificial recharge, and several agencies have purchased from the Bureau of Reclamation large amounts of Class II water (the nonfirm supply) from San Joaquin River when available through the Friant-Kern

Canal or Madera Canal for water spreading or for "replenishment irrigation." By using stream supplies for irrigation and for replenishment of ground water in years of plenty and pumping from wells for irrigation in years of scarcity as well as purchasing canal supplies from the Bureau of Reclamation, several agencies in the San Joaquin Valley are well set for efficient water management.

The permeable materials in the San Joaquin Valley in stream channels, canals, alluvial fans and plains, and soils, which are the most suitable for ground-water recharge, are similar to the permeable materials also abundant and widely distributed in the Sacramento Valley where less is recorded, however, about the achievements and potentialities in ground-water recharge, for water supply is less critical. For example, levees are generally constructed to protect cultivated or urban land from flooding, rather than to hold water on the land for recharge.

Most of the Central Valley has fine-textured soils, with suitable retention of water for crops but not permeable enough for ground-water recharge. In extensive areas where ground water has been pumped for irrigation, the replenishment has been less than the withdrawal over extended periods, and the result has been progressive depletion of storage. (See fig. 6.) The need to know more about recharge has been recognized for many years, and the Central Valley has a long history of research and experiments in artificial recharge. Experiments beginning in 1944 showed (Muckel, 1959) that the rate of infiltration could be increased and sustained over longer periods by various treatments, notably by Bermuda grass or other vegetative cover, cotton gin trash, and other organic residues. Test plots also were used for studies of soil structure and microbiology and the effects of soluble materials and of sediment. It was concluded (Schiff and Johnson, 1966) that successful artificial recharge depends upon the characteristics of the soil and substrata and that the depth, shape, and extent of subsurface control layers determine the usable storage capacity, buildup of the water table, and the likelihood of drainage problems. These conclusions are in accord with findings in many parts of the world that the best recharge areas are generally not ideal for agriculture because they are too permeable to hold soil water for crops. Nevertheless the Central Valley includes extensive areas where both artificial recharge and crops can be sustained by replenishment irrigation, and since 1958 the research and experiments have been increasingly concerned with selection and development of recharge areas and with replenishment irrigation.

Beds of clay or other rock material impermeable enough to create perched ground-water bodies above them or confined (artesian) water beneath them will also inhibit artificial recharge. In the San Joaquin Valley, the Corcoran Clay Member of the Tulare Formation is sufficiently widespread to impede recharge to the confined aquifers that supply large quantities of water for irrigation. The confined aquifers are not replenished as an incidental benefit of irrigation by surface water, even if the water is used lavishly. Artificial recharge of confined aquifers has, however, been achieved directly through recharge wells. The Lindsay-Strathmore Irrigation District in the Tulare Basin was successful in recharging through wells during the first 4 months of 1932, when 1,900 acre-feet (2.3 million m^3) of the winter runoff of the Kaweah River was filtered, chlorinated, and injected into 75 irrigation wells. This water was subsequently pumped out and could be identified by its lower temperature. The experiment lost no wells, pumps, or water and was a success, but it was not repeated because of legal difficulties. Currently 15 wells are being used for artificial recharge by the Delano-Earlimart District in the Tulare Basin.

CONJUNCTIVE USE OF GROUND WATER AND SURFACE WATER

Conjunctive use of ground water and surface water has long been recognized as essential in the California Water Plan. Studies made during the formulation of that plan (California Department of Water Resources, 1957a) indicated that its objectives could not be achieved without full and careful use of the ground-water resources. See also Berry (1962, p. 3.): "The answer for the future thus lies in the full development and use of our ground-water basins, both for conservation of local supplies and for seasonal and long-term cyclic regulation of imported water supplies. This will involve the planned use of ground-water storage in conjunction with surface storage facilities." Several years earlier, the U.S. Bureau of Reclamation (1949, p. 214) had indicated the importance of ground-water development in relation to its Central Valley Project: "In planning and constructing the necessary works [Friant-Kern and Madera Canals] special attention must be given to the problem of using ground-water reservoirs to best advantage. Only by the full use of these underground basins can the irrigable areas of east side upper San Joaquin Valley be developed completely." In California, however, private property rights have been asserted and protected, particularly as to ground water, stemming from the common-law maxim "Cujus est solum ejus est usque ad coelum et ad infernos"—roughly, the landlord owns everything above and beneath his land from heaven to hell. Federal or State agencies thus can lose control of and title to the water they put into ground-water reservoirs: "Leakage from the canal would be quite effective, but how would we collect for it?" (Bain and others, 1966, p. 414). The Bureau of Reclamation, supplying water under contract to several local agencies in San Joaquin Valley, necessarily lines its canals with concrete where they traverse the natural recharge areas of ground-water reservoirs, to prevent "loss" by seepage.

Nor do State agencies have managerial authority over ground-water reservoirs. At a panel discussion of practical considerations in implementing public policy (McGauhey, 1967, p. 78), moderator Harvey Banks asked John Teerink, Deputy Director of the California Department of Water Resources: "How can we bring about the necessity of coordinated operation of long aqueducts and ground water basins to even out aqueduct flows without undue interference with local control of ground water basins?" Mr. Teerink replied: "In determining the need for regulatory storage along the California aqueduct, we looked for surface storage reservoir sites. We did consider that ground storage was a real possibility. But there did not exist, and there does not exist today, any means by which the State can involve itself in ground water basin management, so we had to go to surface storage."

Krieger and Banks (1962) noted that Californians have made relatively few attempts to stretch the available water supplies and have tended to squander them; they pointed out that one means of checking this waste would be a basin management program of ample scope to maximize the use of the State's ground-water basins. This "demands the immediate attention of our courts, lawmakers, local governing bodies, and water distributing entities, the skill and resources of lawyers, engineers, geologists, economists, financiers, and political scientists***." Eight years later the California Water Plan still faced the same impediment (California Department of Water Resources, 1970c, p. 72): "Full realization of such integrated surface water-ground water system operations in areas where the ground water resource is available will require legal and legislative action and social and political acceptance."

This action may be delayed yet awhile. Fortunately, the California legislature has generally supported local initiative in ground-water basin management and also the conjunctive use of surface and ground water. It has passed special legislation when required for the effective operations of public agencies in populous areas, notably the Orange County Water District (Basin No. 8–1 on pl. 1), as well as in rural areas such as the small mountain-rimmed basins included in the Tehachapi–Cummings County Water District (Nos. 5–28, 6–45) (Porter, 1967). Conjunctive use of surface and ground water currently depends heavily upon the conjunctive operations of local agencies, whose dominant concern is ground water, and Federal and State agencies, whose dominant concern is surface water.

With these social and legal handicaps, conjunctive use of surface water and ground water has, nevertheless, been achieved in many places. It has long been recognized and practiced by local agencies whose user-members have rights in modest though significant local resources of both surface water and ground water, for example in Los Angeles, Santa Clara, and Ventura Counties. Smith (1962) summarized the history of the organization of public districts in Santa Clara County (Basin Nos. 2–9, 3–3) and concluded optimistically on future organizations. In other places varying degrees of conjunctive use have been achieved by the actions of (1) carriers and wholesalers of surface water (Federal and State agencies, large municipalities, and regional agencies such as the Metropolitan Water District of Southern California) and (2) local agencies (county water districts, irrigation districts, water conservation districts, water storage districts, and water replenishment districts) who are purchasers, distributors, and retailers of water and who generally act as users' cooperatives in developing water for a specific group of users. These wholesalers and user cooperatives together form a complex and intricate water industry which has been analyzed by Bain, Caves, and Margolis (1966).

Conjunctive use is possible in many areas because the costs of surface water can be set nearly equal to the costs of pumping ground water and can be manipulated to encourage use of surface water in periods of abundance. Thus the Bureau of Reclamation has set the price of Class II (nonfirm) water supply at less than half the price for Class I water, which encourages replenishment irrigation, and Class II water may be available in the preirrigation season for artificial recharge; contracts requiring payment whether the surface water is used or not will encourage use of surface water from canals rather than ground water from wells. Since 1960, the Metropolitan Water District of Southern California has offered Colorado River water for underground replenishment or for agricultural use at prices substantially lower (in 1970 and 1971 about 50 percent) than domestic rates for untreated water.

REDUCTION OF LOSSES BY EVAPORATION

Throughout the California Region, surface reservoirs lose water by evaporation during the dry summer season. In areas of perennial water surplus, this loss is more than offset by precipitation upon the reservoir area during the wet season, resulting in a net gain in an average year. At numerous reservoirs along north coastal streams or in the Sierra Nevada, therefore, the annual evaporation is less than or only slightly greater than average annual precipitation; Lake Shasta on the Sacramento River and Clair Engel Lake on the Trinity River are the largest of these.

In the drainage basin tributary to the Central Valley, 11 of the largest surface reservoirs are close to the valley and at altitudes less than 1,100 feet (330 m) (table 11). These reservoirs are in localities where annual rainfall generally is less than 20 inches (500 mm); evaporation from a standard land pan is more than 60 inches (1,500 mm) and exceeds 108 inches (2,700 mm) a year at San Luis Reservoir, the highest rate measured in the region except in Death Valley. No published calculations or estimates of the volume of evaporation are available from any of these reservoirs, but one reservoir for which such data exist in the southwestern United States is Lake Mead, with a record of reservoir evaporation beginning in 1952. In the first 11 years after records began, the average storage at Lake Mead was about 18 million acre-feet (22 km^3), average reservoir area 118 thousand acres (29 km^2), and annual evaporation about 850,000 acre-feet (1 km^3). After storage began in upstream Lake Powell in 1963, the storage in Lake Mead was reduced to an average of about 15 million acre-feet (18½ km^3), and the annual evaporation decreased 20 percent to about 660,000 acre-feet (0.7 km^3) in 1964–70, inclusive.

Evaporation per unit of water surface at Lake Mead is probably greater than that at the large reservoirs in the Central Valley, for pan evaporation at Boulder City and at Pierce's Ferry, Nev., is greater than that at San Luis Reservoir. Also, it is to be expected that the California reservoirs will ordinarily contain far less than their capacity during the summer months when the rate of evaporation is greatest. Nevertheless, storage in these large lowland reservoirs requires significant sacrifices of water by evaporation. For efficient water management in arid regions, the surface storage of water should be held to minimums of water area and length of exposure, particularly during the hot dry summers.

RECLAMATION OF NONCONSUMPTIVELY USED WATER

Water reclamation may be achieved by processes that are also used in sewage treatment, waste-water treatment, water renovation, or pollution control, although the quality of water reached by reclamation is normally considerably higher than that resulting from treatment intended merely to satisfy water-pollution control standards. Reclamation may include removal of nutrients from urban waste water or agricultural return flows, or other partial demineralization. But the chief objective of water reclamation is, as pointed out by McGauhey (1971, p. 172), the idea that the user of water should return it to the resource essentially unchanged.

TABLE 11.—*Large surface reservoirs in Central Valley*

Basin	Reservoir	Water surface at usable capacity		Water storage (km^3)
		Altitude (m)	Area (km^2)	
Sacramento	Oroville	274	61	4.29
	Folsom	142	45	1.25
	Marysville[1]	104	45	1.23
	Berryessa	134	85	1.97
Delta	New Hogan	217	16	.41
	Comanche	72	32	.53
San Joaquin	New Melones[2]	332	49	2.96
	New Exchequer	264	28	1.27
	New Don Pedro	253	53	2.50
	Millerton (Friant)	176	20	.64
	San Luis and O'Neill	166	61	2.59
Tulare	Pine Flat	293	24	1.29
Total			519	20.93

[1]Authorized for future construction.
[2]Under construction in 1975.

Most of the water now reclaimed in the California Region is returned to ground-water reservoirs by artificial recharge, but substantial quantities are reused directly for agriculture, industry, and recreation (table 12). The Los Angeles metropolitan area has the greatest concentration of population in the California Region and also leads in sewage production, averaging 100 gallons (380 l) per day per capita. Los Angeles County produces about 700 Mgal/d (2.6 million m^3 per day), and Orange County one-fifth as much, for an annual total approaching a million acre-feet (1.2 km^3). Sewage-treatment plants on the coastal plain and near the coast discharge their effluent into the ocean, but many of the inland treatment plants from the time of their construction have produced waters which percolated through the soil and might enter ground-water reservoirs. The City of Pomona has long maintained a water renovation plant which currently produces about 16 thousand acre-feet (20 million m^3) annually of water with dissolved solids less than 700 mg/l, which is used for irrigation and experimentation.

As population and water demand increased after

TABLE 12.—*Reclaimed water*

Number of plants	Principle use of reclaimed water	Quantity (million m^3)
South Coastal subregion, 1966 (McGauhey, 1971, p. 167)		
9	Ground-water recharge by spreading	293
9	Ground-water recharge by injection (barrier to seawater intrusion)	153
4	Industrial use	86
13	Recreational use (parks and golf courses)	18
4	Recreational use (ponds for fishing, boating)[1]	14
6	Agricultural use (irrigation	6
		570
San Francisco Bay subregion, 1970 (California Division of Water Resources, 1971a)		
7	Recreational use (parks and golf courses)	2.0
6	Agricultural use (irrigation)	2.6
		4.6

[1]Also, swimming and water-contact sports at Santee, San Diego County.

World War II, ground-water reservoirs were depleted by pumping and intruded by seawater along the coast, and increasing amounts of water were imported from the Colorado River. Studies during the 1950's led to the conclusion that 40 percent of the sewage then produced could be economically reclaimed, but the mineral quality of the rest was too poor for salvage (California Department of Water Resources, 1961). Thus, the Whittier Narrows Water Reclamation Plant—with Los Angeles County as banker, the Sanitation District of Los Angeles County as designer and operator, Central and West Basin Water Replenishment District as sole customer, and Los Angeles County Flood Control District as water spreader—began operating in 1962 and currently produces for ground-water recharge about 12 Mgal/d (530 l/s) of water comparable with or superior to the water imported from the Colorado River as to dissolved solids, hardness, and price (Parkhurst, 1969). The Los Angeles County Sanitation Districts have now constructed two additional reclamation plants that increase the production to 60 Mgal/d (85 million m^3 annually) and have plans for reclamation exceeding 400 Mgal/d (1.5 million m^3 per day).

The City of Los Angeles has constructed a pilot plant for tertiary treatment of 5 Mgal/d (7 million m^3 annually) of the waste waters from its Hyperion Plant. The reclaimed water, with not more than 700 mg/l dissolved solids and 200 mg/l hardness, will be used for injection into wells at the north end of the city's coastal barrier (Bookman and Edmonston, 1971). (See section "Seawater Intrusion.") Orange County too has been planning for water reclamation and has reached the stage of implementation of its Water Factory 21 in Fountain Valley (Cofer, 1972). This factory includes a plant to reclaim 15 Mgal/d (21 million m^3 annually) of effluent from a secondary treatment plant, reducing dissolved solids from 1,300 to 1,100 mg/l and hardness from 400 to 200 mg/l by tertiary treatment. This reclaimed water will then be blended with an equivalent amount of seawater to be desalted at an adjacent plant, and the product will be put into the ground-water reservoir through a series of injection wells. The 15-Mgal/d reclamation plant and desalination plant are envisioned as prototypes of 200 Mgal/d (276 million m^3 annually) factories that may ultimately be required for southern California.

Water reclamation is further from reality in the metropolitan area around San Francisco Bay, which still receives a considerable volume of untreated wastes; some studies have proposed a water reclamation plant near the head of the bay to collect waste water from several counties (California Region Framework Study Committee, 1971, p. 51).

MAINTENANCE OF WATER QUALITY

Nearly half the surface water and ground water withdrawn for use in the California Region is used nonconsumptively and then becomes wastewater which generally is polluted by dissolved solids, organic residues, sediment, floating debris, or heat. With increasing population and urbanization, ground-water reservoirs are more and more vulnerable to recharge by waste waters from individuals, communities, farms, and industries; the California legislature has seen this potential pollution both as an aspect of the general problem of water pollution and as a specific problem of protecting the ground-water resources. Rather consistently, its policy has been that water-quality control can be most effectively administered regionally and that the basic responsibility for ground-water development and management should rest with local people. Consequently, the Dickey Water Pollution Act of 1949 and later the Porter-Cologne Water Quality Control Act of 1969 set up nine regional water-quality control boards and a coordinating State board.

The Porter-Dolwig Ground Water Basin Protection Act of 1961 provided for studies and plans for "correction and prevention of irreparable damage to, or impaired use of, the ground water basins of this State." This provision was amended in 1967 to require, for local projects, a cooperative agreement between the State and the local agency and substantial participation or cost sharing, or both, by the local agency; thus the California Department of Water Resources can provide technical assistance in assessing the present status of and in considering plans for management of quality and quantity of ground water. The Porter-Cologne Water Quality Control Act of 1969 gave increased powers to the California regional water quality control boards, which may now require adjudication of ground-water rights in order to protect water quality. Also after having the essential data and findings, a regional board may file actions to restrict pumping and impose a physical solution to prevent destruction or irreparable injury to the quality of ground water in a reservoir. Another act of the legislature requires that water well standards be established on the basis of the recommendations of the California Department of Water Resources in areas where necessary to protect water quality; however, the standards are to be established and enforced by the counties and cities in the area.

Clearly, local people can have a dominant voice in the maintenance of water quality in ground-water reservoirs in counties and public districts as owners and users of the land overlying the ground-water reservoir. At the local level, there may be conflict of interest between ground-water users and those who obtain their supplies from other sources but have wastes to dispose of; however, by monitoring the quality in various localities and by providing scientific data and expertise to local agencies, State and Federal agencies should eventually overcome the advantage that the waste-makers have achieved by tradition and the common law.

SELECTED REFERENCES

Alameda County Water District, 1971, Summary report on ground water conditions: 16 p. 7 pl.

Bader, J. S., 1969, Ground-water data as of 1967: U.S. Geol. Survey open-file reports—North Coastal subregion, 11 p; San Francisco Bay subregion, 12 p; Central Coastal subregion, 16 p; South Coastal subregion, 21 p; Sacramento Basin subregion, 16 p; San Joaquin Basin subregion, 16 p; North Lahontan subregion, 8 p; South Lahontan subregion, 25 p; Colorado Desert subregion, 19 p; Summary, California region, 32 p.

Bain, J. S., Caves, R. E., and Margolis, Julius, 1966, Northern California's water industry: Baltimore, Johns-Hopkins Press, 729 p.

Berry, W. L., 1962, Ground water in California's future: Conf. on Ground Water Recharge, 3d, Berkeley 1961, p. 1–14.

Bianchi, W. C., and Muckel, D. C., 1970, Ground-water recharge hydrology: Agr. Research Service Pub. 41-161, 62 p.

Bookman, Max, and Edmonston, R. M., 1971, Annual survey report on ground water replenishment, Central and West Basin Water Replenishment District: Downey, Calif., 80 p.

California Department of Public Health, 1962, California domestic water supplies: Bur. Sanitary Eng., 76 p.

———1968, Investigation of ground water quality problems in Central Basin of Los Angeles Co.: Bur. Sanitary Eng.

California Department (or Division) of Water Resources, 1930, Report to the Legislature on State Water Plan: California Dept. Water Resources Bull. 25, 204 p.

———1946, Salinas Basin investigation: California Dept. Water Resources Bull. 52, 246 p.

———1949, Salinas Basin investigation, basic data: California Dept. Water Resources Bull. 52a, 432 p., 10 pl.

———1950, Sea-water intrusion into ground water basins bordering the California Coast and inland bays: Water Pollution Inv. Rept. 1, 23 p., 2 tables.

———1952, Ground water basins in California: Water-Quality Inv. Rept. 3, 44 p.

———1955a, Oil field waste water disposal, Raisin City Oil Field, Fresno County: Water-Quality Inv. rept., 26 p.

———1955b, Quality of ground water in the Stockton area, San Joaquin County: Water-Quality Inv. Rept. 7, 51 p., 21 pl.

———1956, Geologic and waste disposal investigation, Lost Hills Oil Field, Kern County: Interdepartment commun. 11 p.

———1957a, The California Water Plan: California Dept. Water Resources Bull. 3, 272 p.

———1957b, Sea water intrusion, Report of Los Angeles Flood Control District: California Dept. Water Resources Bull. 63, app. A, 142 p.

———1958a, Sea water intrusion in California: California Dept. Water Resources Bull. 63, 92 p.

———1958b, Quality of ground waters in California 1955–1956: California Dept. Water Resources Bull. 66, 228 p.

———1958c, Reclamation of water from sewage and industrial wastes: California Dept. Water Resources Bull. 68, 44 p.

———1960a, Intrusion of salt water, southern Alameda County: California Dept. Water Resources Bull. 81, 74 p.

———1960b, Lower San Joaquin Valley water quality investigation: California Dept. Water Resources Bull. 89, 189 p., 3 app., 12 pl.

———1961, Feasibility of reclamation of water from wastes in the Los Angeles metropolitan area: California Dept. Water Resources Bull. 80, 155 p., 22 pl.

———1964a, Quality of ground waters in California 1961–1962: California Dept. Water Resources Bull. 66–62, 429 p.

———1964b, Water well standards, Alameda County: California Dept. Water Resources Bull. 74–2, 94 p.

———1964c, Ground water occurrence and quality, Lahontan region: California Dept. Water Resources Bull. 106–1, 486 p.

———1964d, Coachella Valley investigation: California Dept. Water Resources Bull. 108, 180 p.

———1964e, Water use by manufacturing industries in California: California Dept. Water Resources Bull. 124, 154 p.

———1965a, Sea water intrusion, Oxnard Plain: California Dept. Water Resources Bull. 63–1, 100 p.

———1965b, Water well standards, Los Angeles County: California Dept. Water Resources Bull. 74–7, 106 p.

———1965c, Water well standards, San Joaquin County: California Dept. Water Resources Bull. 74–5, 114 p.

———1965d, California State Water Project water supply contracts: California Dept. Water Resources Bull. 141, v. 1, 702 p., v. 2, 598 p.

———1966a, Water well standards, Del Norte County: California Dept. Water Resources Bull. 74–3, 132 p.

———1966b, Santa Ana Gap salinity barrier: California Dept. Water Resources Bull. 147–1, 194 p.

———1966c, Implementation of the California Water Plan: California Dept. Water Resources Bull. 160–66, 143 p.

———1967a, Mojave River ground water investigation: California Dept. Water Resources Bull. 84, 166 p.

———1967b, Ground water occurrence and quality, San Diego region: California Dept. Water Resources Bull. 106–2, 250 p.

———1968a, Sea water intrusion, Bolsa- Sunset area: California Dept. Water Resources Bull. 63–2, 186 p.

———1968b, Water well standards, State of California: California Dept. Water Resources Bull. 74, 224 p.

———1968c, Water well standards, Fresno County: California Dept. Water Resources Bull. 74–6, 16 p.

———1968d, Water well standards, Ventura County: California Dept. Water Resources Bull. 74–9, 84 p.

———1968e, South Bay, Fremont study area, ground water resources: California Dept. Water Resources Bull. 118–1, 136 p.

———1968f, Delano nitrate investigation: California Dept. Water Resources Bull. 146, 196 p.

———1968g, Investigation of waste discharges in the Lompoc Basin: Memo. rept., 85 p.

———1968h, The fate of pesticides applied to irrigated agricultural land: California Dept. Water Resources Bull. 174–1, 30 p.

———1969a, Water wells and springs in the Fremont Valley area: California Dept. Water Resources Bull. 91–16, 157 p.

———1969b, Sanitary land fill studies: California Dept. Water Resources Bull. 147–5, 122 p.

———1970a, Hydrologic data, 1969: California Dept. Water Resources Bull. 130–69, v. 2, Northeastern California, 531 p; v. 5, Southern California, 555 p.

———1970b, Oxnard Basin extraction-type barrier: California Dept. Water Resources Bull. 147–6, 157 p.

———1970c, The California Water Plan—outlook in 1970: California Dept. Water Resources Bull. 160–70, 170 p.

———1970d, Watermaster service in the Raymond Basin: California Dept. Water Resources Bull. 178–70, 58 p.

———1970e, Watermaster service in the West Coast Basin: California Dept. Water Resources Bull. 179-70, 121 p.

———1970f, Sea water intrusion, Lower Salinas Valley: Progress rept., 28 p.

———1970g, Sea water intrusion, Pismo-Guadalupe area: California Dept. Water Resources Bull. 63–3, 82 p.

———1970h, Nitrates in ground waters of San Joaquin Valley: Memorandum rept., 44 p., 4 maps.

———1971a, Hydrologic data, 1970: California Dept. Water Resources Bull. 130–70, v. I, North Coastal area, 55 p.; v. II, Northeastern California; v. III, Central Coastal area, 137 p.; v. IV, San Joaquin Valley, 223 p.; v. V, Southern California.

———1971b, Watermaster service in the Central Basin: California Dept. Water Resources Bull. 180–70, 151 p.

———1971c, Watermaster service in the upper Los Angeles River area: 89 p.

———1971d, Nitrates in ground waters of the Central Coast area: Memo. rept., 15 p.

California Division of Mines and Geology, 1961, Sand and gravel in California, Part A—Northern California: California Div. Mines and Geology Bull. 180A, 38 p.

———1964, Sand and gravel in California, Part B—Central California: California Div. Mines and Geology Bull. 180B, 58 p.

———1968, Sand and gravel in California, Part C—Southern California: California Div. Mines and Geology Bull. 180C, 56 p.

California Division of Oil and Gas, 1972, Oil and gas statistics—statistical tables: v. 58, no. 2, p. 64–151.

California Region Framework Study Committee, 1971, Comprehensive framework study; App. 5, water resources: Pacific Southwest Inter-Agency Comm. 339 p., 41 maps.

California State Oil and Gas Supervisor, 1959 and 1972, Summary of operations, California oil fields: California Div. Oil and Gas, 45th and 58th ann. rep. pt. 2, tables 1, 5, 6, and 7.

California Water Resources Control Board, 1961, Effects of refuse dumps on ground water quality, California Water Resources Control Board Pub. 24, 101 p.

———1965, Dispersion and persistence of synthetic detergents in ground water, San Bernardino and Riverside Counties: California Water Resources Control Board Pub. 30, 97 p.

Cofer, J. R., 1971, Ground water conditions, water supply, and basin utilization: Orange County Water Dist. Engineer's Rept., 53 p., 11 pl.

———1972, Orange County Water District's Water Factory 21: American Soc. Civil Engineers Nat. Water Resources Eng. Mtg., Atlanta, Preprint 1636, 28 p.

Committee on Ground Water, 1961, Ground water basin management: American Soc. Civil Engineers Manual Eng. Practice No. 40, 160 p.

Committee on Water, 1966, Alternatives of water management: Natl. Acad. Sci., Natl. Resource Council Pub. 1408, 51 p.

Conkling, Harold, 1946, Utilization of ground-water storage in stream-system development: Am. Soc. Civil Engineers Trans., v. 111, p. 275–354.

Crooke, H. W., and Toups, J. M., 1962, Ground water basin management and artificial recharge in Orange County: Conf. on Ground Water Recharge, 3d, Berkeley 1961, Proc., 13 p.

Cruff, R. W., and Thompson, T. H., 1967, A comparison of methods of estimating potential evapotranspiration from climatological data in arid and subhumid regions: U.S. Geol. Survey Water-Supply Paper 1839–M, 28p.

Davis, G. H., Green, J. H., Olmsted, F. H., and Brown, D. W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U.S. Geol. Survey Water-Supply Paper 1469, 277 p.

Durfor, C. N., and Becker, Edith, 1964, Public water supplies of the 100 largest cities in the United States, 1962: U.S. Geol. Survey Water-Supply Paper 1812, p. 99-118.

Dutcher, L. C., 1972, Proposed criteria for design of a data collection system for ground-water hydrology in California: Water Resources Research, v. 8, p. 188–193.

Evenson, R. E., 1965, Suitability of irrigation water and changes in ground-water quality in the Lompoc subarea of the Santa Ynez River basin: U.S. Geol. Survey Water-Supply Paper 1960–S, 20 p.

Federal Water Quality Administration, 1970, The economics of clean water: U.S. Dept. Interior, v. 1, p. 18.

Gleason, G. B., 1947, Report to Assembly of the State Legislature on water supply of Antelope Valley*** pursuant to House Resolution 101, 20 p.

Harding, S. T., 1960, Water in California: Palo Alto, N-P Publications, 231 p.

Hunt, C. B., and Robinson, T. W., 1966, Hydrologic basin, Death Valley, California: U.S. Geol. Survey Prof. Paper 494–B, 103 p.

Katz v. Walkinshaw, 141 California 116, 135, 74 Pac. 766 (1903).

Koenig, J. B., 1969, The Geysers geothermal field 1969: California Div. Mines and Geology, Mineral Inf. Service, v. 22, p. 123–128.

Kohler, M. A., Nordenson, T. J., and Baker, D. R., 1959, Evaporation maps for the United States: U.S. Weather Bur. Tech. Paper 37, 13 p.

Krieger, J. A., and Banks, H. O., 1962, Ground water basin management: 50 California Law Rev., p. 56–77.

Lofgren, B. E., 1969, Field measurement of aquifer-system compaction, San Joaquin Valley, California: Internat. Assoc. Sci. Hydrology, Colloque de Tokyo, p. 273–284.

McGauhey, P. H., coordinator, 1967, Practical considerations in implementing public policy, panel discussion: Conf. on Ground Water Recharge, 6th, Berkeley 1967, Proc., p. 34–83.

———1971, Waste water reclamation–urban and agricultural, *in* Seckler, David, ed., California Water: Berkeley, Univ. California Press, p. 161–173.

Miller, G. A., 1969, Water resources of the Marine Corps Supply area, Barstow, Calif. : U.S. Geol. Survey open-file report, p. 33–40.

Miller, R. E., and Singer, J. A., 1971, Subsidence in the Bunker Hill–San Timoteo area, Southern California: U.S. Geol. Survey open-file report, 27 p.

Moreland, J. A., 1972, Artificial recharge in the Upper Santa Ana Valley, Calif.: U.S. Geol. Survey open-file report, 82 p.

Moreland, J. A., and Singer, J. A., 1969, Evaluation of water-quality monitoring in the Orange County Water District, California: U.S. Geol. Survey open-file report, 27 p.

Muckel, D. C., 1959, Replenishment of ground water supplies by artificial means: U.S. Dept. Agriculture Tech. Bull. 1195, 51 p.

Murray, C. R., 1968, Estimated water use in the United States, 1965: U.S. Geol. Survey Circ. 556, 53 p.

Musser, E. H., 1959, Resume of oil field operations in 1959: California Div. Oil and Gas—Summ. Operations, v. 45, no. 2, p. 51–82.

Olmsted, F. H., and Davis, G. H., 1961, Geologic features and ground-water storage capacity of the Sacramento Valley, California: U.S. Geol. Survey Water-Supply Paper 1497, 236 p.

Parkhurst, J. D., 1969, Progress report, Los Angeles County Sanitation District's water reclamation program: Conf. on Ground Water Recharge, 7th, Los Angeles 1969, Proc., 10 p.

Pasadena v. Alhambra, 33 California (2d) 908, 207 (2d) 17 (1949).

Peters, H. J., 1972a, Ground water management: Water Resources Bull. v. 8, p. 188–197.

———1972b, Criteria for ground water level data networks for hydrologic and modeling purposes: Water Resources Research, v. 8, p. 194–200.

Piper, A. M., 1965, Has the United States enough water?: U.S. Geol. Survey Water-Supply Paper 1797, 27 p.

Piper, A. M., Garrett, A. A., and others, 1955, Native and contaminated waters in the Long Beach–Santa Ana area: U.S. Geol. Survey Water-Supply Paper 1136, 315 p.

Pitt, Leonard, 1966, The decline of the Californios: Berkeley, Univ. California Press, p. 1–25, 83–120.

Poland, J. F., 1959, Hydrology of the Long Beach–Santa Ana area, California: U.S. Geol. Survey Water-Supply Paper 1471, 252 p.

———1969, Land subsidence and aquifer-system compaction, Santa Clara Valley, California: Internat. Assoc. Sci. Hydrology, Colloque de Tokyo, p. 12–21.

———1972, Subsidence and its control, *in* Underground waste management and environmental implications—a symposium: Am. Assoc. Petroleum Geologists Mem. 18, p. 50–71.

Poland, J. F., and Davis, G. H., 1969, Land subsidence due to withdrawal of fluids: Geol. Soc. America, Eng. Geol. Rev., v. 2, p. 187–269.

Poland, J. F., Lofgren, B. E., Ireland, R. L., and Pugh, R. G., 1975, Land subsidence in the San Joaquin Valley, California, as of 1972, U.S. Geological Survey Prof. Paper 437–H, 78 p.

Poland, J. F., and Evenson, R. E., 1966, Hydrogeology and land subsidence, Great Central Valley, California; *in* Bailey, E. H., Geology of northern California: California Div. Mines Bull. 190, p. 239–247.

Porter, C. V., 1967, Implementing policies through legislation: Conf. on Ground Water Recharge, 6th, Berkeley 1967, Proc., p. 26–33.

Powell, J. W., 1962, Report on the lands of the arid region of the United States: Cambridge, Mass., Harvard Univ. Press, 196 p.

Powers, W. R. III, 1970, Water-resources inventory Antelope Valley–East Kern Water Agency area: U.S. Geol. Survey open-file report, 15 p.

Price, W. P., and Baker, C. K., 1963, Ground water recharge activities in United Water Conservation District of Ventura Co.: Conf. on Ground Water Recharge, 4th, Berkeley 1963, Proc. 6 p.

Rainwater, F. H., 1962, Stream composition of the conterminous United States: U.S. Geol. Survey Hydrol. Inv. Atlas HA–61, 3 pl.

Rex, R. W., 1971, Geothermal resources in the Imperial Valley, *in* Seckler, David, ed., California Water: Berkeley, Los Angeles, Univ. California Press, p. 190–205.

Richardson, Donald, and Rantz, S. E., 1961, Interchange of surface and ground water along tributary streams in the Central Valley, California: U.S. Geol. Survey open-file report, 253 p.

Richter, R. C., and Chun, R. Y. D., 1961, Artificial recharge in California: Am. Soc. Civil Engineers Trans., v. 126, pt. 3, p. 742–762.

Schiff, Leonard, and Johnson, K. L., 1966, Some physical and chemical considerations in artificial ground-water recharge: Conf. on Ground Water Recharge 5th, Los Angeles 1965, Proc., p. H–60–70.

Smith, S. C., 1962, The public district in integrating ground and surface water management: California Agricultural Experimental Sta., Giannini Found. Research rept. 252, 135 p.

Snyder, J. H., 1955, Ground water in California—the experience of Antelope Valley: California Agricultural Experimental Sta., Giannini Found. Ground Water Studies No. 2, 171 p.

Tannehill, I. R., 1947, Drought, its causes and effects: Princeton, N.J., Princeton Univ. Press, 254 p.

Theis, C. V., 1940, The source of water derived from wells— essential factors controlling the response of an aquifer to development: Civil Eng., v. 10, p. 277–280.

Thomas, H. E., 1962, The meteorologic phenomenon of drought in the Southwest: U.S. Geol. Survey Prof. Paper 372–A, 43 p.

———1969, Water as a resource and as a nuisance: Highway Research Rec. 271, p. 17–28.

Thornthwaite, C. W., 1948, An approach toward a rational classification of climate: Geog. Rev., v. 38, p. 55–94.

Tolman, C. F., Hyde, B. C., and Killingsworth, C., 1931, Ground water supply and saline contamination of Pittsburg and adjacent industrial area: Stanford Univ., 66 p. 8 figs.

U.S. Bureau of Reclamation, 1949, Central Valley Basin: U.S. 81st Cong., Senate Doc. 113, 430 p.

United States Geological Survey, 1966, Mineral and water resources of California, Part I: U.S. 89th Cong., Senate Comm. on Interior and Insular Affairs, Comm. Print, p. 1–450.

U.S. Public Health Service, 1961, Ground water contamination: U.S. Public Health Service Tech. Rept. W61–5.

U.S. Weather Bureau, 1963, Decennial census of United States, monthly average for state climatic divisions, 1931–60, California: U.S. Weather Bur. Climatography of the United States, no. 84–4, 3 p.

Ver Planck, W. E., 1958, Salt in California: California Div. Mines Bull. 175, 164 p.

Waananen, A. O., and Bean, R. T., 1966, Mineral and Water Resources of California, Part 2: U.S. 89th Cong., Senate Comm. on Interior and Insular Affairs, Comm. Print, p. 451–647.

Williams, D. E., and Wilder, D. G., 1971, Gasoline pollution of a ground–water reservoir—a case history: Ground Water, v. 9, no. 6, p. 50–56.